Before the
Federal Communications Commission
Washington, DC 20554

In the Matter of Revision of Part 15 of the FCC's Rules Regarding Ultra-wideband Transmission Systems	ET Docket 98-153

Reply Comments of Time Domain Corporation

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Executive Summary

"Technology is no barrier; old thinking is."

William E. Kennard
February 2, 1999, in *The Hill*

This proceeding offers the Commission the opportunity to cast off old thinking while fulfilling its statutory obligations as spectrum manager and as the federal agency charged with encouraging technological innovation in telecommunications. The Commission has learned five important points from the comments filed in this proceeding.

1) The response to the FCC's Notice of Inquiry was unprecedented. For what has been, until recently, an obscure technology, there were a large number of responses – more than in the spread spectrum proceeding. This interest is reflected in recent articles in the press:

- "… a radical and controversial communications technology that has the potential to make vastly more efficient use of the increasingly precious radio spectrum." *New York Times* [1]

[1] John Markoff, "F.C.C. Mulls Wider Commercial Use of Radical Radio Technology," *New York Times*, December 21, 1998

- " An entirely new technology that could have a tremendous effect in the wireless world…." *Telephony*[2]

- "This technique offers high communications privacy; low likelihood of interference; low cost; high capacity…." *Telecom Insider*[3]

- "[T]he technology has numerous commercial and military applications …." *Aviation Week & Space Technology*[4]

2) The comments from the UWB industry and users of UWB products document the unique value of UWB technology across a diverse universe of applications. There is the potential to create entirely new and beneficial services. The ground penetrating radar industry, with a history stretching back more than two decades, discussed the irreplaceable benefits of UWB. Current users of GPR include law enforcement, utilities, geologists, transportation engineers and maintenance personnel, archeologists, and those concerned with locating land mines all need GPR. Others see the potential to deliver through-wall imaging radars, high performance wireless networks, medical telemetry systems, ultra-high precision location and tracking systems, sensors to improve productivity and safety in the construction industry, and precision radar sensors. As Paul

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[2] Nancy Gohring, "New technology gains support," *Telephony*, January 18, 1999.
[3] , Bennett Z. Kobb, "Ultra-wideband Technology is Ultra Promising," *Telecom Insider*, September 4, 1998.
[4] William B. Scott, "Radar Patent Skirmish Ripples Through Industry," *Aviation Week & Space Technology*, June 15, 1999.

A. Turner, executive director of the Price WaterhouseCoopers Global Technology Center, stated "When you take its attributes and compare it to the competition, you have a very interesting technology that could lead to awesome possibilities."[5]

3) While there are only a small number of UWB products on the market, there are actually billions of devices emitting signals virtually identical to UWB signals without causing harmful interference. The introduction of devices that make use of UWB emission will not add measurably to the ambient noise level. The GPR industry comments documented that some 2000 relatively high power GPR systems have been in use for decades, even at airports. Clearly, their experience strongly suggests these systems do not interfere with incumbent spectrum users, including safety of life aeronautical systems.

4) There is only one band below 10 GHz with a fractional bandwidth in excess of 25%, so there is little unrestricted spectrum into which UWB signals can be shoehorned under the present regulatory structure. Ultra-wideband technology offers an opportunity to make additional use of the spectrum with a technology that in theory should be a more efficient approach to spectrum sharing. Moreover, UWB modulation techniques are often better matched to the propagation channel, allowing effective communication at significantly lower emitted power levels (100 times or more lower within buildings),

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[5] In John Markoff, "F.C.C. Mulls Wider Commercial Use of Radical Radio Technology," *New York Times*, December 21, 1998

thereby reducing the overall RF noise floor. The proposal by Time Domain, the Ultra-wideband Working Group and others represents a non-threatening approach to allowing the introduction of extremely low emitted power devices.

5) With the more rational approach of regulating the impact of emissions and not the "intent", the FCC can allow the introduction of UWB technology while making very few changes to its existing regulations.

The next step for the FCC is to move swiftly to a Notice of Public Rulemaking. The FCC has sufficient input to do this.

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Regulate Impact, Not "Intent"

Emissions into the restricted bands from personal computers, videocassette recorders, and billions of devices with digital electronics are allowed; essentially identical signals from ultra-wideband transmitters are not. Substantially more powerful spurious and other unwanted emissions from intentional radiators in other services are legal, while even the most minute UWB emissions are illegal. A primary component of the debate in this Notice of Inquiry is over semantics. Were the FCC simply to remove the differentiation between "intentional" and "unintentional" emissions, UWB devices that conformed to Class A and Class B emissions limits would become legal without a measurable difference to licensed spectrum users.

Available Spectrum

Under current regulations, there is little bandwidth available for UWB systems. Figure 1 illustrates the amount of bandwidth available within the non-restricted portion of the spectrum. As it shows, there is only one band with a fractional bandwidth of 25% or greater (two if the 24.4% fractional bandwidth band around 2 GHz is included). As most within the ultra-wideband industry stated in their comments to this Notice of Inquiry on Ultra-wideband, ultra-wideband technologies begin to show their value when fractional bandwidths exceed 25%.

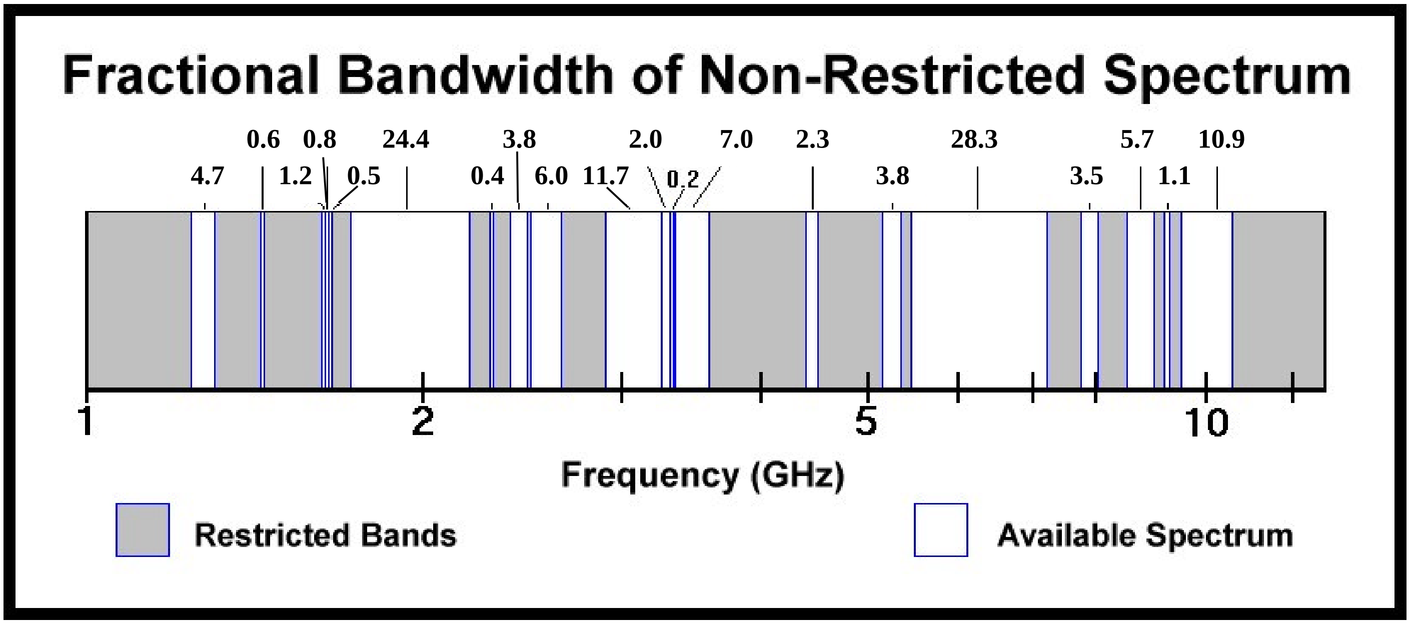

Figure 1. Fractional Bandwidth of Non-Restricted Bands according to the latest version of Section 15.205 of the FCC Rules.

As this graphic so clearly illustrates, and as the FCC recognizes, it is impossible to exploit fully the capabilities of ultra-wideband RF technologies without placing emissions into the restricted bands. If the benefits of ultra-wideband products are to be available to the public safety, consumer, commercial, and industrial worlds, the FCC must revise the wording of its regulations to recognize that it is not the "intent" of the emissions, but the actual impact of those emissions on other users of the spectrum that is important to control.

General Response to All Filed Comments

Time Domain was very pleased with the generally favorable comments that were filed. Many of the comments documented the value and unique capabilities of ultra-wideband techniques to solve critical problems. Moreover, the comments showed that a significant number of UWB users are federal and state government agencies.

The overwhelming majority of comments supported the need for a UWB rulemaking and offered constructive comments to this end. A few comments identified concerns, some of which are addressed in this document. Comments documented applications for ultra-wideband in such diverse fields as:

- Medical applications. Pulson Medical discussed the EMI/EMC problems of using narrowband radios near biomedical instrumentation and how ultra-wideband promises to allow the implementation of non-interfering biomedical telemetry systems. Moreover, by overcoming the constraints of multipath it becomes feasible to achieve higher performance, e.g., longer range, higher data rates, and low transmit powers.

- Consumer communications applications. Interval Research discussed its interest in products for the elderly, educational facilities and high speed data communications, all at affordable prices.

- Automotive applications. AD Little, M/A-COM and TRW discussed the need for automotive sensors for such things as airbag deployment and pre-collision sensing.

(At a time when the federal government is pushing industry to find technologies to allow safer deployment of airbags.)

- Consumer & industrial construction applications. Zircon noted how its products could make construction work more efficient and safer.

- Industrial liquid level gauges. SAAB, Magnetrol, Rosemount, Endress + Hauser, explained how UWB can serve this application better than other alternatives; and

- High performance data communications systems. Time Domain, Multispectral Solutions Inc., and prospective educational users highlighted the prospect for low cost high capacity communication links.

The GPR community was especially well represented with numerous compelling advocates stating that bandlimiting GPR would have a significant negative impact on the value of GPR for which there is no technical alternative. Other comments documented the negative impact that such bandlimiting would have on communications applications.

While there was some divergence on a few technical issues, it is critical to recognize that there was no disagreement on the following significant issues:

- NPRM. Almost all believed that the Commission should move forward with an NPRM quickly, so the public can experience the benefits of UWB technologies and applications.

- Pulse Desensitization. All comments agreed that it would be improper to apply pulse desensitization to measurements of UWB signals.

- Class B Damped Sinewaves. There was again virtually unanimous agreement that this was not an issue with properly implemented UWB systems. (Perhaps one of the best lines in all of these comments dealt with this issue by stating: "The concept of damped waves is obsolete and if such a device should appear (escaped from a museum?) it would anyway be rejected unless the power is very low."[6])

The UWB industry was also nearly unanimous in the following points regarding UWB:

- Bandlimiting and notch filtering UWB products is not feasible as it would significantly degrade product performance.

- Support for the 25% or greater fractional bandwidth definition of ultra-wideband specifically because signals with that property have, as a result, unique characteristics relative to traditional narrowband signals. Among these characteristics are that at any particular center frequency, these system have the highest possible radar resolution achievable and relatively large processing gains.[7]

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[6] See SAAB Comments, pg. 8.
[7] See TDC Comments filed on December 7, 1998.

GPR Specific Comments

A large number of respondents submitted information documenting the long history of ultra-wideband "Ground Penetrating Radars" (GPR). **Moreover, not one stated an awareness of having caused harmful interference.** While this anecdotal evidence is not sufficient to prove the case for allowing large scale use of ultra-wideband devices, it certainly bolsters the various analyses which show that the probability of harmful interference from low power ultra-wideband devices is extremely small.

Time Domain found the following statements from the GPR community particularly noteworthy:

- "No other non-destructive technique can provide such a rapid and accurate assessment of the conditions of concrete structures. GPR has been used to find voids under airport runways, in tunnel walls, in buildings and parking structures, and in historical monuments." [Geophysical Survey Systems, Inc.]

- "[A]s a geophysics professional, I view any restrictive regulation of subject geophysical methods [i.e., GPR] as potentially crippling to realizing the overall capabilities of geophysics for contributing to solution of nationally significant problems and requirements." [D. K. Butler, Research Geophysicist, Texas A&M University]

- "Ground penetrating radar has the highest resolution of any tool for noninvasive subsurface investigation. It is one of the very few tools capable of seeing nonmetallic things in the subsurface like organic chemical contamination, plastic land mines (humanitarian demining), plastic natural gas pipes, mapping fine scale soil structure necessary to foster plant growth in agriculture. It is one of the vital tools in the toolbox of geophysicists, with many beneficial uses." [G.R. Olhoeft, Professor of Geophysics, Colorado School of Mines]

- "The FBI and RCMP [Royal Canadian Mounted Police], as well as local law enforcement agencies have used [GSSI GPRs] to locate bodies." [Geophysical Survey Systems, Inc.]

- "[T]he US Federal Government spends about $60,000,000/year on ground penetrating radar applications or research…." He also notes that there have been two "Ground Penetrating Radar Government Users Conferences." [G.R. Olhoeft, Professor of Geophysics, Colorado School of Mines]

- "I personally have applied GPR in airports, nuclear power plants, military installations, D.O.E. facilities…." [Mr. Thomas Fenner of MALA Geoscience USA]

- While Lawrence Livermore National Laboratory did not mention it in its comment, it recently sold at least one GPR system to the Federal Highway Administration for several million dollars.[8]

Clearly, agencies within the Federal Government have long recognized the value of GPR and know that GPRs are safe to use.[9] Moreover, it appears to Time Domain that had the ultra-wideband industry not attempted to gain regulatory legitimacy, the federal government would have been happy to continue to allow ground penetrating radars to operate so long as they kept a "low profile".

While Time Domain recognizes the importance of the ultra-wideband ground penetrating radar application and fully supports the development of regulations that encompass the GPR application, Time Domain is not presently involved in ground penetrating radar (GPR), so our knowledge of the requirements for successful GPR operation is limited. Therefore, Time Domain's reply comments are not meant to include GPR applications unless specifically stated.

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[8] See: www-lasers.llnl.gov/idp/mir/files/warhus_spie/spiepaper.html and www.bts.gov/ntl/DOCS/peres.htm.

[9] Moreover, Time Domain has spoken with scientists and engineers at the U.S. Army's Night Vision Laboratory and its Aberdeen Proving Grounds, at Los Alamos National Laboratories, and at Sandia National Laboratories. All are working with UWB radars with relatively large instantaneous power signals, some with instantaneous powers in the low giga-Watt levels.

Comments Regarding the Restricted and Broadcasting Bands

Time Domain observes that the comments expressing concern over emissions within the restricted bands were based primarily on misinformation and miscalculations or lack of understanding of the Part 15 rules and limits. The concerns voiced over emissions within the restricted bands were based upon fear of the unknown, rather than scientific evidence. Small amounts of energy within a band do not necessarily lead to harmful interference. This is evidenced everyday by the functioning of televisions and systems that use the restricted bands while in the presence of a multitude of unintentional and spurious in-band emissions (and UWB ground penetrating radars as well).

Time Domain was surprised by the comments from the Consumer Electronics Manufacturers / National Association of Broadcasters and Broadband Telecom Systems. During the development of the current Part 15 regulations, the television broadcasting and consumer electronics industry approved these field strength limits as being sufficient protection. The comments from CEMA/NAB even quote the FCC report on Part 15 saying, "The general emission limits contained in 47 C.F.R. 15.209 are applied to the unwanted emissions produced by most other Part 15 devices. They were developed with the specific intent of preventing interference to television reception and have proved to be effective in this regard."[10] These latest comments imply that the television industry seeks

[10] See CEMA/NAB Comments, footnote 6.

protection greater than current levels. However, this seems irrational since the membership of the Consumer Electronics Manufacturers Association includes companies such as Compaq Computer Corporation, Hewlett Packard Company, and IBM. If the Consumer Electronics Manufacturing Association were in fact advocating a more restrictive limit it would be advocating a significant increase in manufacturing costs for computer and other digital device manufacturers, which is not needed and totally unwarranted, solely to benefit the manufacturers of televisions (who, it should be noted, also produce products that must be approved as being compliant with the same Part 15.109 limits as of 6/23/99 [11]). Moreover, the emissions from UWB devices resemble those of digital devices[12], and therefore, if at the same limits would cause no more interference to television receivers than computers and their peripherals.

The American Radio Relay League calculations were erroneous. In Appendix A[13] of the ARRL comments, there are several parameters that do not resemble any UWB system that would be authorized under Part 15. With the current Part 15 limits, which have been proposed by the UWB Working Group as appropriate limits for unlicensed UWB operations, the electric field strength allowed would be 200 uV/m at 3m in a 120 kHz bandwidth (for frequencies between 212 and 960 MHz). This is equivalent to an EIRP of

[11] See section 15.37, by 6/23/99 TV receivers will have to meet Class B limits. Prior to this date, they have been allowed 10 to 20 dB higher limits than Class B.
[12] See Time Domain and Interval Corporation's time and frequency domain data provided in their Comments.
[13] See Appendix A of ARRL.

12 nW in a 120 kHz bandwidth, or 0.1 nW per kHz (-70 dBm/kHz). The transmit power used in the ARRL calculations was 1 mW in a 1 MHz bandwidth (worst case), with a transmit antenna gain of 33 dBi [14], which is an equivalent EIRP of 3 dBm/kHz, which is 73 dB over the current and proposed Part 15 limits! It appears that the ARRL commentators did not understand the current Part 15 limits and measurement technique, in which the transmit antenna is an integral part of the field strength measurement. The current Part 15 measurement techniques and limits would not allow for only a transmit power measurement with an unlimited transmit antenna gain, as suggested by ARRL. Moreover, amateur radio receivers in this band already contend with a large proliferation of digital devices whose emissions are mostly concentrated below 1 GHz, and also are operating on a secondary basis and sharing the 420-450 MHz band with federal government operations as well as other amateur operators which are allowed EIRPs of several hundred Watts. Time Domain understands that other amateur radio interests such as Tucson Amateur Packet Radio (TAPR) organization have studied UWB and support the technology.

There were comments filed regarding maintaining the integrity of the GPS bands (US GPS Council, FAA, and TEM Innovations). These comments are based on an incomplete appreciation of what most of the UWB industry has requested and also fail to consider

[14] A parabolic dish with 33 dBi gain at approximately 430 MHz has a diameter of over 32 feet, and would be impractical for almost all applications.

the limitations on emissions into the GPS bands from electronic devices allowed by Part 15 rules. At the levels requested by Time Domain and other participants in the UWB Working Group, UWB devices would not significantly increase the noise floor in the GPS bands. Both Interval and Time Domain provided emissions data (time and frequency domains) that highlighted the similarities between UWB impulse signals and emissions from digital devices. The limits being requested by the UWB Working Group are the same as those for Part 15 digital devices, which are already allowed into the GPS bands, as well as all other restricted bands (and with significant proliferation as well). This issue is not limited to just this UWB proceeding. Within the last year the FCC published an NPRM of RF lighting devices and a Report and Order on Global Mobile Personal Communications by Satellite (GMPCS) both dealing with the issue of safe broadband emission levels for operation within the GPS band.[15] The levels specified by the FCC as being adequate to protect against harmful interference is 500 uV/m at 3m for 1 MHz, or the approximate equivalent EIRP of –40 dBm measured in 1 MHz. Devices such as RF lighting sources have a significant potential not only to proliferate but also to be concentrated in areas such as parking lots or office buildings. These limits have proven to provide adequate protection from digital devices and are now being applied to other wideband emissions, and Time Domain believes these levels to be appropriate for UWB devices as well. Furthermore, these levels are actually lower than what is allowed

[15] See FCC ET Docket No. 98-42 and GEN Docket No. 98-68.

for out-of-band emissions from PCS service, which now numbers multiple millions of portable units.[16] For a 600 mW portable, the allowable out-of-band emissions is about 85 uW measured in 1 MHz (-10.7 dBm per MHz), which is approximately 30 dB or a factor of 1000 times greater power allowed than the current general Part 15 limit and these emissions are allowed in the GPS bands as well as other restricted bands.

The Federal Aviation Administration's specific comment regarding potential harmful interference between a UWB device and GPS indicates that they are misinformed about the results of the FCC's simple test of the impact on a GPS receiver from the signal of a Time Domain Part 15-qualifiable radar. Time Domain has performed a GPS test and analysis, which is attached in Appendix A, which was later independently confirmed by the FCC OET Lab. For the FCC test, the emissions from the radar prevented the receiver from tracking when the separation distance was less than a foot and it prevented acquisition at a separation distance of less than ten feet. Similar GPS interference can be seen from testing devices such as pagers and Motorola's popular walkie talkies.[17] In addition to studying the effects of a single TM-UWB device, Time Domain has attached in Appendix B a cumulative analysis modeled to study the effects of three different common sensitive aviation receivers, GPS being one of them. (It is also worth noting

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[16] See Section 24.238 in the Commission's Rules.

[17] Time Domain Corporation's Waiver Request, Appendix F, submitted on February 2, 1998.

that MSSI listed in their appendix that some of their UWB devices operated in the GPS band without interference and had an integral GPS receiver built in.)

The FAA raises the specter of interference to mission critical aviation communications and navigation systems without providing any characterization of the susceptibility of these systems to in-band emissions. Time Domain is sensitive to these concerns and has done analyses and has reviewed data that indicate no significant problem. Time Domain has also reviewed the FAA data and has found serious and substantial errors in their arguments. Time Domain is particularly concerned that the FAA does not present scientifically valid arguments to support their claims. The FAA has cited interference incident reports that they assert are representative of anticipated problems from UWB devices. Time Domain has seen a copy of a FAA report on a long range ultra-wideband radar that caused interference to FAA systems. In this case a military radar system was emitting hundreds perhaps thousands of watts in relatively long swept frequency pulses. These signals do not resemble the emissions being proposed by Time Domain or others within the UWB industry. Rather, most UWB manufacturers are advocating allowing intentional emission of signals that are equal in terms of power spectral density to the allowed emissions from digital devices such as computers and electronic toys. The FAA comment implies that all of these devices have the potential to cripple the aeronautical communications and navigation system. Essentially, the FAA would have everyone believe that the five million Furby toys[18] sold last Christmas pose a threat to aeronautical systems.

TEM Innovations also indicated concern over interference to FAA radars.[19] The analysis provided by TEM compares the interference potential of an individual Part 15 device against two FAA radars, regardless of whether the device was an UWB system or just 'ultra-wideband' emissions from an unintentional radiator or out-of-band emissions from intentional radiators. A long term, on-going experiment provides overwhelming evidence that these levels do not cause harmful interference to such radars. The experiment is in fact the everyday operation of these radars in the presence of millions upon millions of Part 15 devices around urban areas and airports.

There are several explanations for the obvious discrepancy between TEM's simplistic model and reality. The beam shape and inclination of the radar's antenna, as well as that most of these radars rotate or synthetically scan, are critical factors in estimating the true impact of in-band emissions. TEM's model assumes that the antenna is always pointed directly at a Part 15 device, whether on the ground, or in a building. While it is possible to point these radars at shallow angles above the horizon, ground clutter will degrade performance much more than the low power emissions of a Part 15 device. (Besides, given the high transmit powers typical of radars, it may be dangerous to point radar

[18] Furby toys have been shown to exceed the general limits specified in Part 15.
[19] See TEM Innovations Comments, pg 8.

beams towards the ground.) In fact, the NTIA manual, in the general section of 5.5.1, encourages that useful receiver techniques be employed "for reduction of the susceptibility of radars to low-duty-cycle pulse interference", which is what a Part 15 device would appear as to a rotating FAA radar. Since it is unlikely that the Part 15 emitter will be in the main beam and since radars typically scan over large arcs, the impact of in-band emissions is even further lessened. (It would seem likely that there would be numerous reports of GPRs causing interference, since many GPRs have been used for decades at airports and military airbases.)

In further support of the insignificance of Part 15 level UWB emissions, Appendix B evaluates the potential impact of multiple, co-located Part 15 devices operating within buildings. It concludes that even large numbers of time modulated ultra-wideband emitters will not have an impact. For all the reasons cited above, it is clear that calculations provided by TEM Innovations are overly simplified, such as assuming only free space losses. This is an issue that will most likely be seen in the future as others try to argue that emissions from devices meeting the Part 15 limits are deleterious, yet do not properly incorporate the real world in their analyses.

Definition of UWB (Wideband vs. Ultra-Wideband)

While Time Domain and many others support a definition of UWB based solely on fractional bandwidth with the lower limit being 25%, some disagreed. RF engineers tend to think that 1 GHz is a very wide bandwidth, however, for operation in the 100's of GHz, 1 GHz is narrowband – it is all a matter of perspective. XtremeSpectrum's discussion on definition of UWB technology, that ultra-wideband RF issues are scalable, is on target:

> "The motivation for preferring definitions based on bandwidth relative to center frequency follow from two primary desirable features. The first is immunity to scintillation and multipath. The only way to prevent scintillation (speckle or multipath fading…) is to have resolution that is approximately equal to the wavelength."[20]

Some have rationalized a definition that does not consider fractional bandwidth above 10 GHz because it may not be feasible to build antennas at such frequencies[21]. However, we at one time heard these same claims about UWB antennas for frequencies below 10 GHz, yet practical antennas have been designed.

Others appear to be proposing definitions that lead to competitive advantages, i.e., creating a regulatory barrier to entry. Comments from SAAB, MSSI and TEM presented arguments for definitions that would harm most UWB technologies by presenting applications for which there was no overriding need for UWB, i.e., applications where reduced radar resolution and processing gain were acceptable. These comments discussed wideband techniques that are already possible within the existing rules and, as such,

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[20] See XtremeSpectrum, Inc. Comments pg. 5.

[21] See Zircon Comments, pg.3.

really do not belong in this proceeding. (It should also be noted that frequently MSSI misapplied the term "UWB" to wideband signals, e.g., a 30 MHz bandwidth signal centered at 1.33 GHz; this could lead to some confusion among readers.[22]) TEM's recommendation that changes be made to rules specific to the NII band should be considered within that proceeding, not this proceeding on ultra-wideband.

Comments from MSSI and TEM claimed that wideband techniques can be substituted for ultra-wideband techniques without any performance penalties. (Time Domain finds this an odd claim on the part of MSSI, since most of the equipment that MSSI shows in its appendix of MSSI products has fractional bandwidths in excess of 25%.)

It is clear, despite these two comments, that wideband techniques can not be substituted for UWB in all applications without performance penalties. For example:

- As noted in the comments filed by the GPR industry, limiting the bandwidth of a radar signal degrades the resolution of the system. Since some applications need resolution of a few inches and must penetrate the ground or into structures, only UWB techniques are viable as only UWB techniques have both sufficient bandwidth and a low operating frequency.[23]

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[22] See MSSI Comments, pg. 9.

[23] For example, L.M. Frazier, "Radar Surveillance through Solid Materials", SPIE Photonics East Conference, Enabling Technologies for Law Enforcement and Security, Boston, MA, November 18-22, 1996, paper 2938-20, documents the one-way (continued)

- For in-building and other cluttered area geo-location systems, reducing bandwidth decreases range resolution. Given the time dispersion signals experience within buildings and in urban areas, it is crucial to have the ability to time resolve multipath to within less than a nanosecond, if high performance is expected. Waveforms with multiple zero crossing, as would result from filtering a UWB signal, complicate the determination of time of arrival. Additionally, it is desirable to have this bandwidth at a relatively low frequency to minimize the impact of building materials.[24]

- In communication systems, reducing the bandwidth decreases processing gain. Processing gain is necessary to overcome Rayleigh fading, the bane of radio systems. This is especially a problem within buildings and in urban areas. Moreover, in-building and urban area communication systems that transmit multi-megabits per second need all the processing gain that can be achieved. MSSI gives as an example a 20 Mbps data link operating on a 500 MHz bandwidth signal. MSSI calculates the processing gain to be 25 which equals 14 dB. Were the system to have 2 GHz of bandwidth, processing gain would then be 20 dB. This 6 dB difference is huge when one considers the impact of multipath and the needs of a multiple access communications system. MSSI's statement "The system's fractional bandwidth of

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losses cause by common building materials. It documents the value of lower frequencies for through wall surveillance.

[24] See for example: Pahlavan, K, et al, "Wideband Radio Propagation Modeling for Indoor Geolocation Applications", IEEE Communications Magazine, April, 1998, pps. 2 – 7. Also, L.M. Frazier, Op. Cit.

8.8% is irrelevant in terms of the ability to either accommodate the high data rate or counteract multipath effects" is simply not supportable with theoretical or experimental results.[25]

MSSI's statement that "UWB systems have not demonstrated high processing gains for several reasons, the primary ones being clock timing inaccuracies and relative platform motions" suggests that MSSI's motives for its comments stem from limitations in its technical approach and not to limitations inherent in all UWB approaches. Time Domain achieved high processing gains, exceptional timing[26], and insensitivity to motion years ago.

In summary, the applications on which the comments from SAAB, MSSI and TEM are focused do not require the high performance available from efficient, high performance UWB systems. Rather they are developing wideband systems, not UWB systems, and these types of systems are adequately covered by existing rules. Their recommendations are outside of the scope of this proceeding.

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[25] See for example: Win, M.Z. and Scholtz, R.A., "Ultra-Wide Bandwidth Signal Propagation for Indoor Wireless Communications", IEEE International Conference on Communications, Montreal, Canada, June, 1997, pg. 56 to 60.

[26] See for example, Larson, L. et al, "A Si/SiGe HBT Timing Generator IC for High Band-width Impulse Radio Applications", to be presented at 1999 Custom Integrated Circuits Conference. The circuit described is only the latest implementation by Time Domain.

Impulse vs. Stepped Frequency

Some commentators, notably SAAB, have stated that the question of energy radiated in the restricted bands may be dealt with by the implementation of UWB with frequency agile systems, which would simply not dwell within the restricted bands. While this suggestion has merit for implementation of UWB systems for some applications, limiting UWB to this technique would be contrary to the FCC goal of facilitating the fullest development of technology. Different techniques for implementing UWB have advantages and disadvantages in addressing specific applications, system implementations must have access to the optimum UWB implementation to meet their goals or requirements. Any rules, which result from FCC action following this NOI proceeding, must allow for the fullest development of UWB technology. This means accommodating all methods of generating UWB signals within any rules; swept-frequency, stepped-frequency, short pulse, impulse and perhaps, other methods as yet undeveloped must be accommodated.

Highlighting the difference between two types of UWB systems, impulse systems and stepped frequency systems, shows how these two techniques are suited to different applications and further emphasizes the advantages of ultra-wideband techniques over narrowband techniques.

- Impulse systems can be implemented at lower cost. Impulse generation of ultra-wideband waveforms is exceptionally simple and low cost. It is feasible to build subnanosecond multi-gigahertz bandwidth impulse generators for a few dollars. Stable stepped frequency generators with similar bandwidths and stability are significantly more expensive.

- Impulse systems have excellent clutter rejection. Stepped frequency systems can not deal with saturation of the LNA, in short-range, high clutter environments which can result from reflections off nearby objects, when a radar is trying to “see” more distant objects (similar to spread spectrum’s near/far problem). Impulse systems are much more immune to such reflections because they are time gated. A strong return from a nearby object may cause momentary saturation of the system’s LNA, but it quickly returns to linear operation. The LNA on an early prototype through-wall radar built by Time Domain was saturated for approximately 2 ns after pulse firing due to antenna coupling, but was linear thereafter. It could, thus, be in contact with walls, but still detect objects just a couple of feet away on the other side. Therefore, impulse systems are generally better for clutter-limited applications.

- Stepped-frequency systems have better dynamic range. Receivers in stepped-frequency systems have a lower noise floor due to their narrower bandwidth. The necessarily wider bandwidth of impulse systems increases the input equivalent noise of the receiver, thus reducing dynamic range. Therefore, stepped-frequency systems may be better for noise-limited applications.

- Impulse systems require simpler data processing. For stepped frequency systems, complex processing needs to occur involving Fourier transforms. For time domain, or impulse techniques, the processing essentially involves simple addition and subtraction.

- All types of UWB systems will suffer performance degradation if portions of the spectrum corresponding to the restricted bands are eliminated. The ability of a UWB system to tolerate this degradation is dependent upon both the system and data processing requirements related to a specific application.

Limits and Aggregate Impact

Those who worry about Class A and Class B level emissions should remember the EIRP for Class B emissions equals (at 3 meters for frequencies above 1 GHz):

- 75 nW/MHz
- -71 dB_W/MHz
- 75 fW/Hz
- -131 dB_W/Hz

This is a minute amount of power, especially when there are billions of devices already legally emitting at these power levels.

Appendix B examines the aggregate impact on three aviation receivers including GPS for various urban environments. The conclusion of this analysis is that UWB signals at Class A and B power levels, even in very large concentrations with in buildings, will not cause harmful interference to aviation. These conclusions are obvious when one considers the numbers and concentrations of Part 15 devices that exist throughout the United States. Consider Pixar, the computer animation company that produced such movies as "A Bug's

Life" and "A Toy Story". Their facility in the San Francisco area has approximately 1000 microprocessors made by Sun Workstation all linked with a very high speed local area network within a single room. Similar concentrations of workstations, monitors, etc. can be found in Wall Street trading rooms. Or consider a city like Boston with its large concentration of universities and students, each most likely with a computer. Yet, the FAA is not deluged with interference incident reports involving FCC compliant digital devices.

Some of the comments expressing concern about the aggregate effect have missed the phase component in the aggregate equation. While some almost imply that multipath will create power out of thin air,[27] UWB signals, like frequency domain spread spectrum signals, add non-coherently like noise and will not have this coherent 20 Log additive impact. In short, these signals are not coherent due to several factors, including but not limited to: systems operating with different PRF (pulse repetition frequencies), different start times and asynchronous clocks, varying distances from the transmitters, and in some cases, a noise encoding or time dithering.

[27] See MSSI Comments, pg.12-13.

Measurement Technique

Time Domain was pleased to read that most of the comments regarding measurement techniques agreed on many of the major issues. There was some deviation as to the specifics of the technique amongst those advocating standard frequency domain methodologies, such as the current techniques and power spectral density approaches. Others proposed using measurement techniques based on time domain instrumentation, which will be shown to be impractical for standard testing.

Inapplicability of Pulse Desensitization

The most significant point to highlight is that there was unanimous agreement that the pulse desensitization factor is inappropriate, because it incorrectly exaggerates potential interference.[28] *Hence, the industry consensus is that it* _not_ *be applied to UWB measurements.*

Peak Limit

As for the 20 dB peak limit over the average limit, there appeared to be some confusion. Several comments looked as though they believed the peak measurement or limit had to be 20 dB over the average measurement, and thus fixing the duty cycle. To clarify for

[28] See comments of Time Domain, UWB Working Group, WINForum, Interval Research, XtremeSpectrum, TEM Innovations, Zircon, Endress + Hauser, M/A-COM.

the record, the rules state that the limitation of peak emissions is 20 dB greater than the average limit. Therefore, the peak measurement can be up to, but not greater than 20 dB over the average limit (not the measurement).[29] Time Domain suggests that the Commission reword this section in the rules to lessen the confusion. The need for a peak limit 20 dB over the average limit is to guard against very low duty cycle transmissions whose emissions might have sufficient power to cause the front ends of victim receivers to become non-linear.[30] This is the essence of M/A Com's statement that "Notwithstanding the comments by Time Domain Corporation, it is difficult to see that operation in excess of 20 dB peak to average power is threatening to the operation of other equipment unless the peak power itself is high enough to be a threat."[31] Typical interference analysis focuses on the ratio of the average power of the interfering signal to average power of thermal noise. Having a peak measurement with a higher limit makes sense because analyzing the peak power of the interfering signal to the average power of the thermal noise, as done by WINForum[32], would overstate interference potential. Comparing the peak interference to average thermal does not account for the peaking effects of the thermal noise floor nor does it account for the potential intermittent effects of the emitter's peaking. Typically, systems can withstand intermittent errors but not continuous degradation. Historically, the Part 15 peak limit, 20 dB above the average

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[29] Section 15.35 of the Commission's Rules.

[30] Endress & Hauser, pg. 6. M/A Reply Comments, pg.1 & pg.5.

[31] See M/A-Com Reply Comment, pg. 5.

[32] Wireless Information Networks Forum (WINForum), Attachment 2, pg. 5

limit for frequencies above 1 GHz, has proven to be effective. In the absence of a better proposal, it seems necessary to retain this peak limit.

Time Domain and the UWB Working Group proposed to maintain the current peak limit of 20 dB over the average limit given that the measurement technique resemble that of the current average and peak methodologies, which do not include a correction by calculation for duty cycle (assuming pulse desensitization is not applied).

Impracticality of Measurement Techniques in the Time Domain

In ANRO's filing, this misunderstanding of peak and average was compounded by a misunderstanding of the purpose of measurements of the emissions from ultra-wideband systems. ANRO and Lawrence Livermore National Laboratory recommended[33] that measurements of ultra-wideband systems be conducted in the time domain. The purpose of spectral measurements specified in Part 15 is to ensure that emissions from digital devices are unlikely to interfere with licensed users. Since, the systems, which are to be protected, are frequency domain systems, frequency domain measurements are proper. A time domain measurement technique would not be practical because of the limit structures, which are different over specified frequency ranges. In addition, not all of the UWB systems being proposed are impulse or short pulse technologies. Measuring stepped frequency or CDMA based UWB technologies with a time domain technique

[33] ANRO Engineering Comments, pg. 3. LLNL Comments, pg. 7.

would be unrealistic. The frequency domain measurement technique is the only one that is versatile enough for all different UWB methodologies. There is also an additional practical reason for avoiding implementation of time domain techniques: certification measurement laboratories are not equipped with high performance time domain measurement systems, have no experience with them, and it would be very costly for them to be so equipped. Frequency domain measurements are necessary and sufficient.

Power Spectral Density Measurements

A large number of comments agreed that the appropriate measurement technique for UWB devices involves a power spectral density (PSD) measurement.[34] Time Domain agrees with this general consensus, and wants to highlight that the current average and peak measurements are, in a manner, power spectral density measurements. The current techniques, which are what the UWB Working Group has proposed, measure the peak and average electric field strength over a 1 MHz bandwidth (a spectral density measurement). However, WINForum expressed concern that a power spectral density measurement utilizing only a single bandwidth would not adequately estimate potential interference from UWB systems. This position is at odds with the technique used in the UNII bands, which requires a single PSD measurement with a 1 MHz bandwidth. Systems operating in UNII bands have bandwidths on the order of 100 MHz, which is

[34] WINForum, etc.

significantly larger than the 1 MHz measurement bandwidth, and would cause peaking effects similar to those discussed in WINForum's UWB NOI comment. Yet, WINForum supported this approach as adequate to protect against harmful interference in the UNII bands.

The comments of WINForum concluded that the general limits and current measurement procedures for unlicensed devices as described in Part 15 are not adequate for estimating interference potential. Their reasoning revolved around the notion that the current limits adequately protect only receivers that operate with the same bandwidth as the measurement instrumentation. The analysis provided in their comments is focused on the measurement procedure itself not on limits, and therefore, their statement that the general limits are inadequate is not well substantiated. If WINForum is concerned about Part 15 limits within the UNII bands, they should consider the amount of power that is allowed to systems operating under the UNII rules compared to Part 15 general limits:

- in 5.15 - 5.25 GHz band, it would take over 33,000 UWB devices to equal the EIRP of a single UNII device

- in 5.25 – 5.25 GHz band, it would take about 170,000 UWB devices to equal the EIRP of a single UNII device

- in 5.725 – 5.825 GHz band, it would take about 670,000 UWB devices to equal the EIRP of a single UNII device

WINForum also has a misconception about the types of interference sources. They state that "currently, potential interference sources typically have their energy confined to a narrow frequency range. A victim receiver therefore tends to be affected only by devices with energy concentrated near the receiver's center frequency. However, with UWB devices, this is not the case because of the large UWB bandwidth." This statement is simply not the case due to the overwhelming amount of digital devices, and incidental radiators (especially with DC motors) that emit ultra-wideband signals[35]. Time Domain also contends that narrowband interference, because it is more intelligible, is often more destructive than the noise-like TM-UWB signals. Consequently, their conclusions would seem to implicate that the entire measurement procedure for every Part 15 device be shifted to their approach (since many unintentional radiators are 'ultra-wideband' emitters).

The technique that WINForum has proposed involves performing power spectral density measurements over multiple resolution bandwidths (RBW), from 3 kHz to 30 MHz. Their comments discuss both "power spectral density" and "burst power spectral density", however, the differences between them are not entirely clear. In addition, WINForum did not include information about which measurement detector and analyzer settings they are suggesting be utilized in their approach. Time Domain assumes they

[35] See Appendix C for plots of emissions from computer motherboard, hairdryer, and electric razor – all common devices.

represent a similar structure as the current peak and average measurements, in which, the term "power spectral density" represents an average measurement of the PSD, and "burst power spectral density" a peak measurement of the burst PSD.

Time Domain agrees with the concept of power spectral density measurement and understands the concept of measurements using multiple resolution bandwidths. Nonetheless, Time Domain stresses the importance of both peak and average measurements, even in the context of a PSD approach. When the video bandwidth (VBW) is equal to or greater than the RBW, and a peak detector is used, the analyzer will record the peaking effects observed using that particular RBW. If the VBW is then decreased a great deal (still using a peak detector)[36], the filter effectively smoothes or averages the output of the IF filter. Both measurements are important in estimating potential interference, giving the average emissions over a bandwidth and an estimate of the peak effects. These measurements are then compared to their respective limits. Time Domain suggests that if the Commission decides to use multiple bandwidths for testing that the standard resolution bandwidths of 1 MHz and 120 kHz be used, for the reasons given below.

[36] See the following FCC document for a description of the measurement technique: www.fcc.gov/Bureaus/Engineering_Technology/Orders/1997/fcc97114.txt

The multiple PSD technique that WINForum has suggested may have some interesting theoretical analysis, but in practice will be nearly impossible to implement. The problems that Time Domain sees in carrying out the WINForum procedure are:

- WINForum notes that because of the RBW limit of spectrum analyzers, any RBW over 1 MHz will require information from the manufacturer and then calculations depending on the pulse repetition rate and the "type" of signal (for instance, time dithered, or coded using pulse position modulation). However, WINForum did not consider that short pulse or impulse techniques are not the only methodologies being proposed by the UWB community. Therefore, tables or equations will be needed for impulse systems using different coding or modulation techniques and with varying PRFs, as well as stepped frequency systems, swept frequency systems, UWB CDMA techniques, "noise" radars, possible hybrid systems, and future new UWB methodologies. It is easy to see that this becomes very complicated, and impractical for test labs to handle.[37]

- Most certification laboratories use spectrum analyzers to measure emissions above 1 GHz, which have a great deal more flexibility than test receivers. However, this is not required, and in fact, there are only four required resolution bandwidths: 200 Hz,

[37] Time Domain has first hand experience seeing that many test labs do not have the training or expertise to handle out corrective calculation factors. We have been to four FCC certified test labs, and only one understood or applied a pulse desensitization correction factor, which is simple compared to the approach WINForum is suggesting.

9 kHz, 120 kHz, 1 MHz.[38] Calling out measurements that are not ANSI standardized will yield differing results. Additionally, many of the labs will not have the required instrumentation to perform these measurements.

- The current equipment used by FCC certification laboratories, both hardware and its software control, are not equipped for multiple PSD measurements. Further, the laboratories are not experienced in this approach. If the Commission mandates multiple PSD techniques (especially with RBW>1MHz), it will necessarily require a great deal of training and new equipment for many of the labs.

- In performing emissions scans with very small resolution or video bandwidths, the time required to perform such a test can be substantial. Imagine having to perform multiple PSD measurements using several small RBW bandwidths, then having to drop the VBW as well for an average measurement, then having to do each of these for different polarizations and frequency ranges. It is obvious that the process could become extremely time consuming and the volume of data overwhelming especially considering the ultra-wide bandwidths used by the UWB systems. For example, the standard measuring process for evaluating a device operating above 1 GHz requires the use of three antennas at two polarizations each for a total of six measurement passes. Below 1 GHz, both peak and Q-Peak measurements are performed, above 1

[38] See ANSI C63.2-1987 and ANSI C63.4-1992.

GHz, peak and average measurements are performed. The total number of measurements made is twelve. At approximately one-half hour per measurement, this requires a total test time of 6 hours. If measurements must be repeated using multiple bandwidths, the time required, data collected, and the cost become almost unmanageable. If a few PSD measurements are to be performed, then a 1 MHz RBW/VBW should be used first to identify the maximum areas, which should be scanned in further detail.

The goal of developing a measurement technique is to produce a standard procedure that minimizes measurement complication to ensure correct implementation, as well as minimize the number of special measurement processes for different systems, while adequately evaluating emissions over certain frequency ranges. This coupled with appropriate limits protects against potential harmful interference. As with any process, there is a tendency to add intricate details in an attempt to "optimize" the procedure. It appears that WINForum, in an effort to cover every contingency, is recommending an overly complicated technique; that would be impractical to carry out. The current approach used throughout Part 15 (including the UNII bands) has been successful and provides satisfactory estimation of potential interference.

The two issues, limits and measurement technique, are coupled and must be developed in parallel, as WINForum has also recognized. The limits have no inherent meaning without an understanding of how the UWB device is to be measured. An NPRM should propose both limits and corresponding measurement techniques.

Conclusion

As a result of the FCC's changes to its regulations a decade ago, there is now a large spread spectrum industry. In comparison to the interest in spread spectrum at a similar stage of development, the interest in ultra-wideband is unprecedented. Simple changes, rapidly made could yield growth for yet another industry that could address many publicly beneficial uses. It is incumbent upon the FCC to initiate and complete a rule making quickly so that it may continue to fulfill its mission to foster innovation.

There were excellent, thoughtful comments from a diverse group. Nearly all of the comments at least recognized the unique promise of ultra-wideband systems, while the GPR industry noted that ultra-wideband had been delivering on some of this promise for decades. This same group also documented that the Federal government and airports were major users of ground penetrating radars and that none was aware of having caused harmful interference.

The comments of the GPR industry lent additional credibility to the various analyses that showed there was no rationale for the concern over cumulative effects from UWB devices. As does the fact that billions of digital devices are already in operation within the limits requested by a majority of the UWB industry.

That same majority agreed that a fractional bandwidth definition of UWB made the most sense, that it did not make sense to apply a pulse desensitization factor to measurement of UWB signals, and that UWB signals were not damped sine waves.

Several paths are open to the FCC that would allow the introduction of very low RF power UWB devices. The simplest would be to eliminate the distinction between intentional and unintentional/spurious emissions and to make corresponding changes elsewhere to compensate for this change.

Appendix A

Test Results & Theoretical Analysis of Compatibility between a Global Positioning System and Time-Modulated Ultra-Wideband Emissions

Introduction

This appendix focuses on the guard range required to prevent harmful interference to a Global Positioning System (GPS) receiver from a time-modulated ultra-wideband (TM-UWB) transmitter. These estimates may not apply to other ultra-wideband systems because emissions from other technologies may not exhibit the noise-like characteristics of TM-UWB systems. This appendix is divided into two sections. The first section describes a measurement. The second provides a theoretical estimate of the required guard range for the civilian GPS band for the proposed electric field strength limit of 500 uV/m at 3m. In so doing, it helps to confirm the theoretical estimate.

Compatibility Test

Measurement Approach

This measurement was used to determine the range when a TM-UWB transmitter operating near Part 15 Class B limits impacts a commercial off-the-shelf GPS receiver. The receiver used was a typical Motorola handheld GPS receiver. It was used in a typical operation by keeping the device relatively level at a normal operating height. The test was performed by allowing the GPS unit to acquire five satellites while the TM-UWB radar was forty five feet away. The TM-UWB transmitter was then walked in slowly. The distance between the TM-UWB transmitter and GPS unit is measured each time the GPS unit lost lock on a satellite. It should be noted that other devices, such as a pager that were tested would also cause the GPS receiver to lose lock on satellites. The tests were performed in a relatively open field north of the 8.5 m tall Time Domain Corporation building, Huntsville.

The GPS system requires a lock on three satellites to give reliable positioning information. The GPS unit is considered to fail when it can not maintain lock on three satellites simultaneously.

The specifications of the TDC TM-UWB radar are summarized in Table 1. The emissions of this device are approximately 1.8 dB below Part 15 Class B limits when the field strength measurements are not adjusted for pulse desensitization. Both vertical and horizontal polarization of the TM-UWB transmitter were tested.

characteristic	value
center frequency	2000 MHz
bandwidth	1700 MHz
pulse repetition rate	5 MHz
average transmit power	6 uW
antenna gain	7 dBi
antenna polarization	both vertical and horizontal
dither coding	pseudo-random dither over 20 ns

Table 1. Specifications of Time Domain Corporation TM-UWB transmitter.

Measurement Results

The data results of both polarization trials are summarized in Table 2.

status change	Distance for horizontal polarization	Distance for vertical polarization
lost lock on fifth satellite	10 feet	10 feet
lost lock on fourth satellite	10 feet	6 feet
lost lock on third satellite	**4 feet**	**6 feet**
lost lock on second satellite	4 feet	3 feet

Table 2. GPS satellite tracking performance versus TM-UWB and GPS seperation.

Theoretical Estimate

This section is divided into three parts. The first part develops the equations used for the analysis. The second part uses these equations to estimate the required guard range. The third part gives an example procedure for estimating the guard range.

Equation Development

The theoretical estimate is based on the prediction in a NAVSTAR manual[39], but the equations have been modified to accommodate their application to ultra-wideband signals. Modifications and assumptions are noted where appropriate.

The analysis begins by defining the thresholds for a given performance state as listed in Table 3. The pertinent thresholds are acquisition, and code tracking and data demodulation. Acquisition is the GPS ability to acquire and lock onto a satellite transmission it does not have a lock on. Code tracking and data demodulation is the ability to maintain lock onto the GPS signal and decode the GPS information. Code tracking and data demodulation is generally referred to as simply "tracking" and will be referred to as such through the rest of this report.

State	$(C/N_0)_{min.}$
Acquisition	34 dBHz
Tracking (Code Tracking & Data Demodulation)	26 dBHz

Table 3. Signal-to-Noise Density thresholds for civilian GPS receiver.

[39] NAVSTAR GPS User Equipment - Introduction, the "NATO-TEAM" at NAVSTAR-GPS Joint Program Office, developed 1986-87, modified 1990.

The performance without any interfering signals is determined by assuming only thermal noise. Equation 1 shows how the signal-to-noise density can be calculated. The civilian GPS system was designed so that the signal strength at the terminals of an isotropic (G_{sv} = 0 dBi) GPS antenna would be -130 dBm at the end of the satellites' life cycle. Table 4 shows typical values for some of the variables. Typically, the satellites will transmit between 3 to 7 dB more power, which helps compensate for the non-hemispherical coverage of the antennas, ambient noise, and blockages (e.g. foliage). Thus, the GPS links' fading margin for acquisition is between 3 dB and 7 dB and, since the required signal-to-noise ratio for tracking is 8 dB lower, the GPS links fading margin for tracking is between 11 dB and 15 dB.

Equation 1

$$\frac{C}{N_0} = \frac{S \cdot L_1 \cdot G_{sv}}{k \cdot T_{sys}}$$

where;

C - total received signal power from satellite (W),
N_0 - thermal noise density of the GPS receiver (W/Hz),
S - received GPS power (W),
L_1 - implementation loss of the GPS receiver,
G_{sv} - GPS antenna gain towards satellite,
$k = 1.30 \cdot 10^{-23}$ W/K Hz - Boltzmann's constant,
T_{sys} - system noise temperature (°K)

Variable	Value
B_G	2 MHz
$P_a \cdot B_G$	60 dBHz
S	-160 dBW

Table 4. Parameters for civilian GPS (see Equation 2 for variable definitions).

In the presence of interference or jammers, the noise density increases as the jamming signal adds to the thermal noise. Equation 2 shows how the jamming signal increases the noise density. This equation has been modified with respect to the NAVSTAR reference because the GPS antenna gain in the direction of the jamming signal is accounted for later in estimating the guard range. The jamming signal received by the GPS is dependent upon several factors including orientation, antennas, separation, etc. Equation 3 has been developed to estimate the UWB jamming signal in very general terms. The equation relies on an isolation term to account for free space losses, antenna gains, etc. This general term is used so that the equation may be applied using theoretical free space losses or by measuring the coupling between the jamming antenna and the GPS antenna. The ratio of bandwidths has been included to account for the spreading benefits of the ultra-wideband signal. This benefit results from the UWB transmission having a much wider bandwidth than the GPS bandwidth. Equation 4 is found by substituting Equation 3 into Equation 2 and solving for I_{UG}, the isolation from UWB transmitter to the GPS receiver.

Equation 2

$$\frac{C}{N} = \frac{S \cdot L_1 \cdot G_{sv}}{k \cdot T_{sys} + J/(P_a \cdot B_G)}$$

where;

C - total received signal power from satellite (W),
N - total noise density of the GPS receiver (W/Hz),
S - received GPS power (W),
L_1 - implementation loss of the GPS receiver,
G_{sv} - GPS antenna gain towards satellite,
$k = 1.38 * 10^{-23}$ W/K Hz - Boltzmann's constant,
T_{sys} - system noise temperature (°K),
J - jamming power at GPS receiver (W),
P_a - GPS jamming processing attenuation,
B_G - GPS system bandwidth (Hz)

Equation 3

$$J_u = \frac{P_{tU}}{I_{UG}} \cdot \left(\frac{B_G}{B_U} \right)$$

where,

J_u - jamming UWB power at GPS receiver (W),
P_{tU} - transmit power from UWB transmitter (W_{EIRP}) ,
I_{UG} - isolation from UWB transmitter to GPS,
B_G - GPS bandwidth (Hz),
B_U - UWB bandwidth (Hz)

Equation 4

$$I_{UG} = \frac{P_{tU} \cdot \left(\frac{B_G}{B_U} \right)}{P_a \cdot B_G \cdot \left(\frac{S \cdot L_1 \cdot G_{sv}}{\left(\frac{C}{N}\right)_{\min}} - k \cdot T_{sys} \right)}$$

where;

I_{UG} - isolation from UWB transmitter to GPS,
P_{tU} - transmit power from UWB transmitter (W_{EIRP}),
B_G - GPS bandwidth (Hz),
B_U - UWB bandwidth (Hz)
P_a - GPS processing gain,
S - received GPS power (W),
L_1 - implementation loss of the GPS receiver,
G_{sv} - GPS antenna gain towards satellite,
$k = 1.38 * 10^{-23}$ W/°K Hz - Boltzmann's constant,
T_{sys} - system noise temperature (°K),
$\left(\frac{C}{N}\right)_{\min}$ - threshold for desired operation (Hz)

These isolation requirements can be used to determine the range at which GPS will no longer be usable. This range is estimated by calculating the distance required such that the link losses are equal to the required isolation. For a conservative estimate, we will assume free space losses only, even though smooth earth losses are more practical. The loss due to free space propagation can be calculated from Equation 5. For example, the free space loss over 1 m for 1.575 GHz is 36 dB. The equation for the guard range can be found by solving for the range and replacing the free space losses with the required isolation and is given by Equation 6.

Equation 5

$$L_{fs} = \frac{1}{\frac{1}{4p r^2} A_e (G_n = 1)} = \left(\frac{4p r f}{c} \right)^2$$

where; L_{fs} - free space loss (dB),
r - range (m),
f - frequency (Hz),
$c = 3 \cdot 10^8$ m/s - speed of light in vacuum,
A_e (G_r) - effective area of antenna of an isotropic antenna (m^2),
G_n - GPS antenna gain towards UWB transmitter, estimated to be 1.

Equation 6

$$R_{guard} = \frac{c}{4p\ f} \cdot \sqrt{I_{UG}}$$

where; R_{guard} - guard range (m),
$c = 3 \cdot 10^8$ m/s - speed of light in vacuum,
f - frequency (Hz),
I_{UG} - isolation from TM-UWB transmitter to GPS (linear)

Results of Theoretical Analysis

This section provides the theoretical isolation range for a TM-UWB system operating at Part 15 Class B (general) limits. The TM-UWB transmit power was determined empirically after a RadarVision radar unit was tested for Part 15 Class B levels with the assumption that pulse desensitization would be waived. The analysis was performed using Equation 4 to calculate the required isolation for a TM-UWB system at Class B field strength limits. The required guard ranges were then calculated using Equation 6. The next section gives an example calculation of this process.

Table 5 shows the values and results of the required isolation and guard range for a 2 GHz TM-UWB transmitter from a civilian GPS receiver for both acquisition and tracking.

state	acquisition	tracking	
P_{tu}	-13.8	-13.8	dBm EIRP
B_g	2.0	2.0	MHz
B_u	2000	2000	MHz
$P_a \cdot B_g$	60	60	dBHz
S	-160	-160	dBW
L_1	-1	-1	dB
G_{sv}	0	0	dBi
T_{sys}	530	530	ºK
$(C/N)_{min}$	34	26	dB/Hz
I_{ug}	62.4	53.4	dB
f	1575	1575	MHz
R_{guard}	19.8	7.1	m

Table 5. Theoretical isolation and guard range requirements for Civilian GPS from a 2 GHz TM-UWB system, assuming free space losses only.

Sample Calculations

The following are a pair of calculations using the development presented previously. These are based on using Equation 4 and Equation 6. In order to estimate the guard range, first the required isolation between the TM-UWB system and the GPS receiver is calculated; then, the range that yields this isolation given free space losses only is determined.

Equation 7 [40]

$$I_{UG} = \frac{P_{tU} \cdot \left(\frac{B_G}{B_U}\right)}{P_a \cdot B_G \cdot \left(\frac{S \cdot L_1 \cdot G_{sv}}{\left(\frac{C}{N}\right)_{\min}} - \left(1.38 \cdot 10^{-11} \frac{m\mathrm{W}}{°\mathrm{K\,MHz}}\right) T_{sys}\right)}$$

$$= \frac{42\,m\mathrm{W} \cdot \left(\frac{2\,\mathrm{MHz}}{2000\,\mathrm{MHz}}\right)}{1\,\mathrm{MHz} \cdot \left(\frac{10^{-10}\,m\mathrm{W} \cdot (0.79) \cdot 1}{2.512 \cdot 10^{-3}\,\mathrm{MHz}} - \left(1.38 \cdot 10^{-11} \frac{m\mathrm{W}}{°\mathrm{K\,MHz}}\right) \cdot 530\,°\mathrm{K}\right)}$$

$$\boxed{I_{UG} = 1.74 \cdot 10^{6} = 62.4\,\mathrm{dB}}$$

Equation 8

$$R_{guard} = \frac{3 \cdot 10^{8}\,\frac{\mathrm{m}}{\mathrm{s}}}{4p\ f} \cdot \sqrt{I_{UG}}$$

$$= \frac{3 \cdot 10^{8}\,\frac{\mathrm{m}}{\mathrm{s}}}{4p\ (1575\,\mathrm{MHz})} \cdot \sqrt{1.74 \cdot 10^{6}}$$

$$= \frac{3 \cdot 10^{2}\ \mathrm{m\ MHz}}{4p\ (1575\,\mathrm{MHz})} \cdot \sqrt{1.74 \cdot 10^{6}}$$

$$\boxed{R_{guard} = 19.8\ \mathrm{m}}$$

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[40] $P_a \cdot B_G$ = 60 dBHz, NAVSTAR GPS User Equipment - Introduction, the "NATO-TEAM" at NAVSTAR-GPS Joint Program Office, developed 1986-87, modified 1990, page G-7.

Conclusion

A theoretical estimate of the guard range required for commercial GPS and TM-UWB transmitter operating at Part 15 Class B limits are 19.8 m for acquisition, and 7.1 m for tracking and demodulation. An experiment indicated that the GPS tracks fewer than three satellites at a distance of 1.8 meters.

The discrepancy between the theoretical model and the measurement can be easily accounted for. As discussed earlier, the satellites are at the beginning of their lifecycle, so they transmit between 3 to 7 dB more power than is specified. In addition, once the GPS receiver has acquired the signal, it requires 8 dB less power to track it. The net result is that the GPS receiver on tracking has between 11 and 15 dB margin. Also note, the radar was 1.8 dB below the Part 15 Class B limit to allow for electric field measurement error, which is typical practice. The combination of the radar being nearly 2 dB below the limit and the excess tracking margin of greater than 10 dB, easily explains the 8 dB difference between the theoretical and experimental results. This means that the theoretical model proposed gives a very conservative estimate of the required separation. Further, in practice the required separation distance can be lessened by utilizing special pulse timing techniques that GPS receivers have more immunity to. Time Domain has used this technique for some military products which dropped the separation distance by a factor of 4.5 (13 dB).

Appendix B

Cumulative Impact of TM-UWB Devices & Affect on Three Aviation Receivers

written by Dr. Jerry Raines

INTRODUCTION

This report describes calculations concerning the total electromagnetic radiation from multiple Time Domain Corporation transmitters. Of particular interest is the power incident upon various avionics receivers in an aircraft flying low over an urban environment. Taking into account the shielding effectiveness (SE) of the floors and ceilings in office buildings, it will be shown that thousands, if not tens of thousands, of emitters can operate before reaching the sensitivity levels of these avionics.

The calculations were performed using an analytic model that was reported in December, 1991. The derivation of that model, excerpted from that report, is included as Attachment A. Briefly, the original model represented various environments as cylinders. Depending upon the dimensions of the cylinder, that shape could model a tall building, a sprawling building, or an entire populated area. Propagation within and around the cylinder was modeled using the extensive measurements of Okumura[41], at a frequency very near the Time Domain Corporation frequency of interest here.

For the present report, the model was extended to include stacks of cylinders, or wafers. Each wafer in the stack is separated by an attenuating slab. This accounts for the SE of floors and roofs as reported by Owen and Pudney[42]. For example, Exhibit 1 shows the model for a 25-story office building, one of the environments of interest here.

DESCRIPTION OF THE COMPUTATIONS

Three different avionics receivers and two different emitter environments were considered. The receivers were chosen from a longer list shown in Exhibit 2. We chose what appear to be the worst case receivers, in terms of sensitivity and/or bandwidth. They are: 1) voice communication; 2) DME (Distance Measuring Equipment); and 3) GPS (Global Positioning System). It is seen that we consider both aircraft voice communications and aircraft navigation. For those receivers which operate on many channels, we selected the lowest frequency because, according to our model, that is the

[41] Okumura, Y. et al, "Field Strength and Its Variability in VHF and UHF Land-Mobile Radio Service", Reivew of the Electrical Communications Laboratory, Volume 16, Numbers 9 – 10, September – October, 1968, pps. 825 – 873.

[42] F.C. Owen and Pudney, "In-Building Propagation at 900 MHz and 1650 MHz for Digital Cordless Telephones", 6th International Conference on Antennas & Propagation, ICAP 89, pgs 275-281.

worst case. So, our computations should provide a good indication concerning whether aircraft safety is affected.

The two different environments are: 1) outdoors throughout an urban environment with radius 8,000 meters and height 50 meters; and 2) indoors throughout the 25-story office building shown in Exhibit 1.

In all cases, the aircraft was 300 meters above the environment. Within a congested (i.e., urban) area, Federal Aviation Rules require a minimum clearance of 1,000 feet between aircraft and structures below. We brought the aircraft about 100 feet lower than that, mostly for the sake of round numbers; however, in practical flying a 100-foot altitude error may well occur.

Also in all cases, two different emitter powers were considered, 50 microwatts and 200 microwatts. These correspond to consumer and industrial applications, respectively (Class B and Class A limits). The power is radiated uniformly over a 2 GHz bandwidth.

Voice Communications

Exhibits 3 and 4 show the computational results for the voice communications receiver. It is seen that thousands of 200-microwatt emitters can operate simultaneously before the net power reaches the sensitivity of the receiver. In the case of 50-microwatt emitters, tens of thousands of emitters can operate. Thus, there is little chance that aircraft voice communication will be interrupted.

DME Receiver

Exhibits 5 and 6 show the computational results for the DME receiver. Due to the low sensitivity of the receiver, it is seen that over one-million emitters may still operate simultaneously indoors or outdoors.

GPS Receiver

GPS receivers are very broadband and extremely sensitive compared to the previous two receivers. The permanently installed receive antennas, however, are mounted on top of the aircraft fuselage. Even the portable units available for general aviation feature antennas that are mounted with suction cups to the windshield. Therefore, in any case, the antenna is shielded by the fuselage from ground based emissions. The shielding is substantial.

Exhibit 7 shows the computed radiation pattern of a GPS antenna with radiation center 0.15 meters (about 6 inches) over a 4-meter diameter fuselage. This is intended to model a typical small commuter plane. It is seen that the SE at the underside of the fuselage is greater than 30 dB. Even if the plane is banked 30 degrees, which would be a steep turn for a scheduled airline, the SE is still greater than 30 dB.

Using a SE of 30 dB, Exhibits 8 and 9 show the computational results for a GPS receiver. It is seen that tens of thousands of emitters can operate simultaneously both indoors and outdoors before their cumulative radiation reaches the sensitivity of the GPS receiver.

CONCLUSIONS

Exhibit 10 summarizes the results of the computations. It is seen that either indoors or outdoors, thousands, if not tens of thousands, of emitters may operate simultaneously without affecting either aircraft communications or navigation. The reasons agree with intuition. Outdoors, the devices are widely dispersed and space attenuation limits the cumulative radiation at any single receiver. Indoors, the attenuation of floors and ceilings compensate for the concentration of devices within a single building.

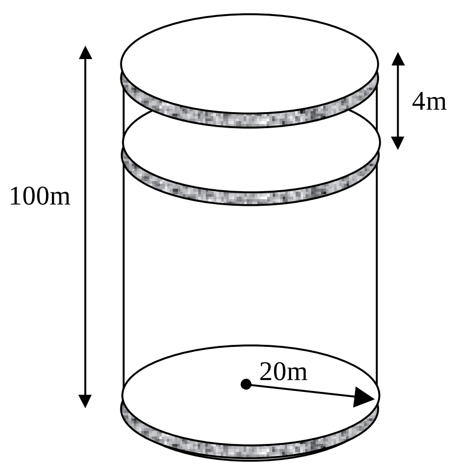

Exhibit 1. Geometry of a 25-story building. Each floor introduces attenuation.

Receiver \ Characteristic	Frequency MHz	Bandwidth MHz	Sensitivity MHz
Voice	**118**	**0.025**	**-103**
DME	**962**	**0.300**	**-85**
VCR	**108**	**0.020**	**-81**
NDB, ADF	**0.190**	**0.012**	**-41**
ILS Localizer	**108**	**0.010**	**-41**
ILS Glide Slope	**329**	**0.034**	**-56**
GPS using C/A Code	**1600**	**2**	**-133**

Exhibit 2. Summary of avionics receivers and their properties. The three worst cases (voice, DME, and GPS) were chosen for detailed analysis.

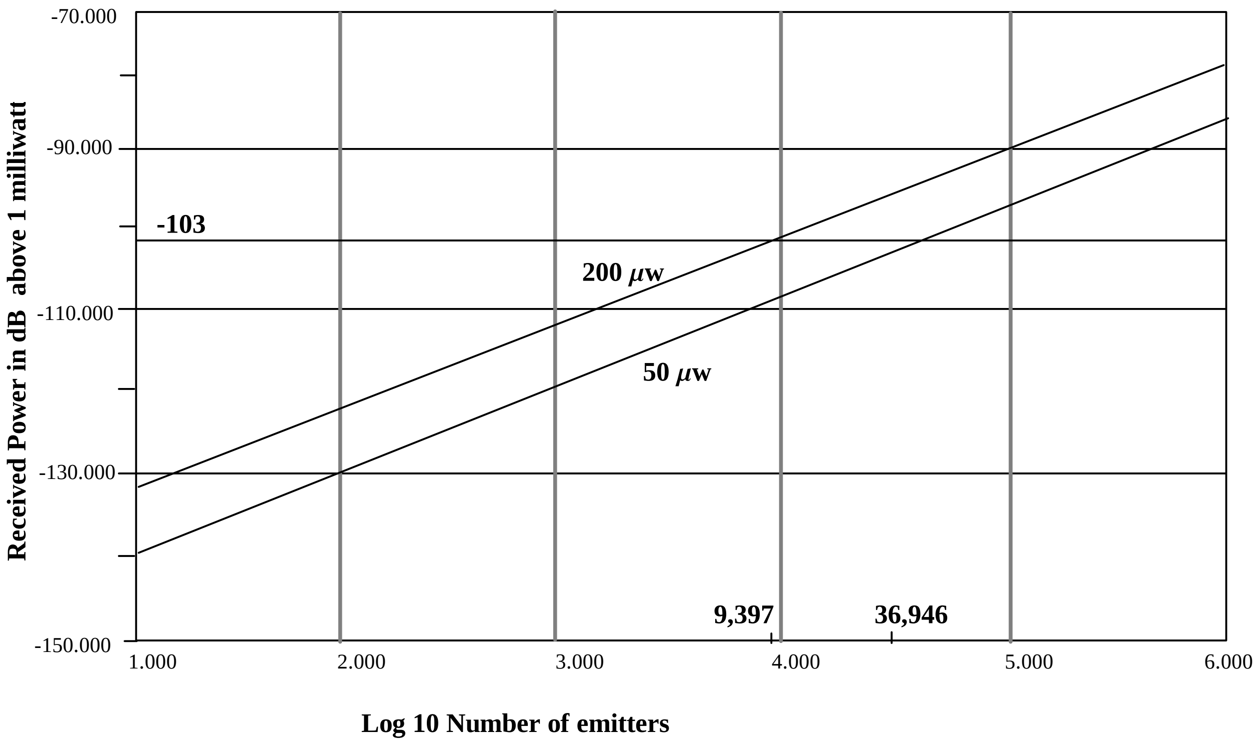

Exhibit 3. Computational results for voice receiver 300 meters above an open urban environment.

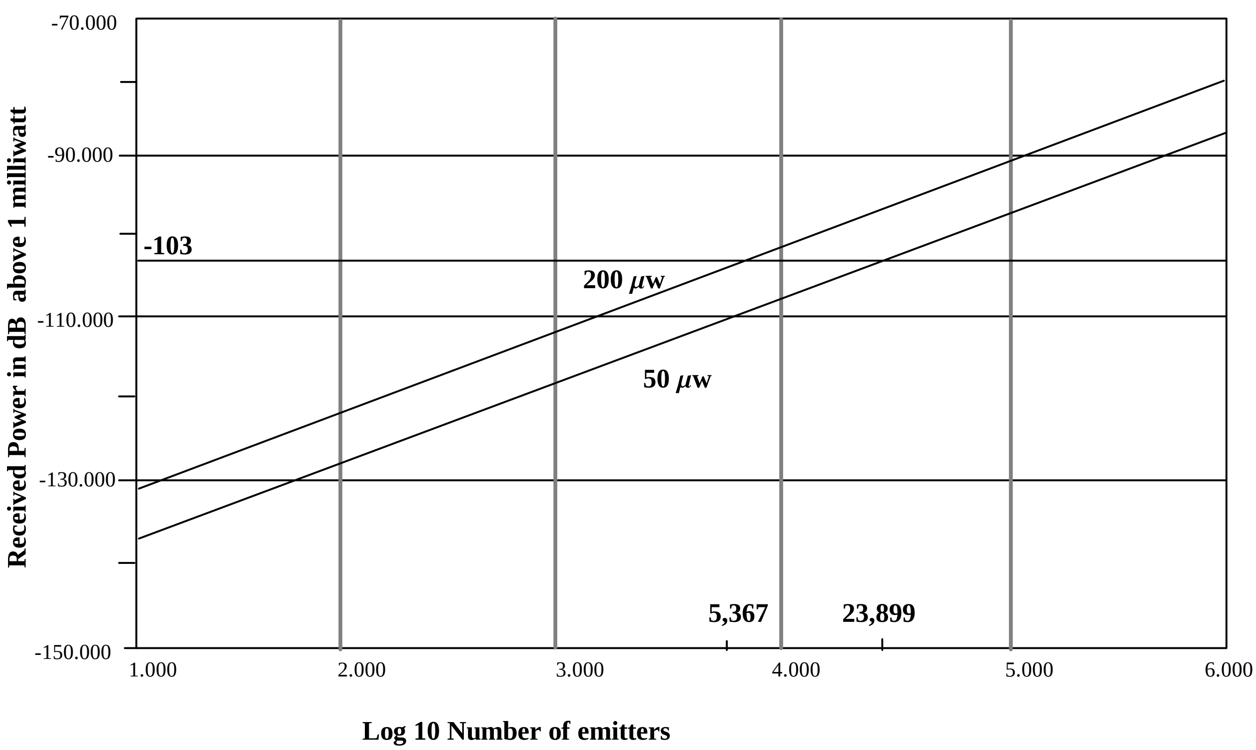

Exhibit 4. Computational results for voice receiver 300 meters above a 25-story building.

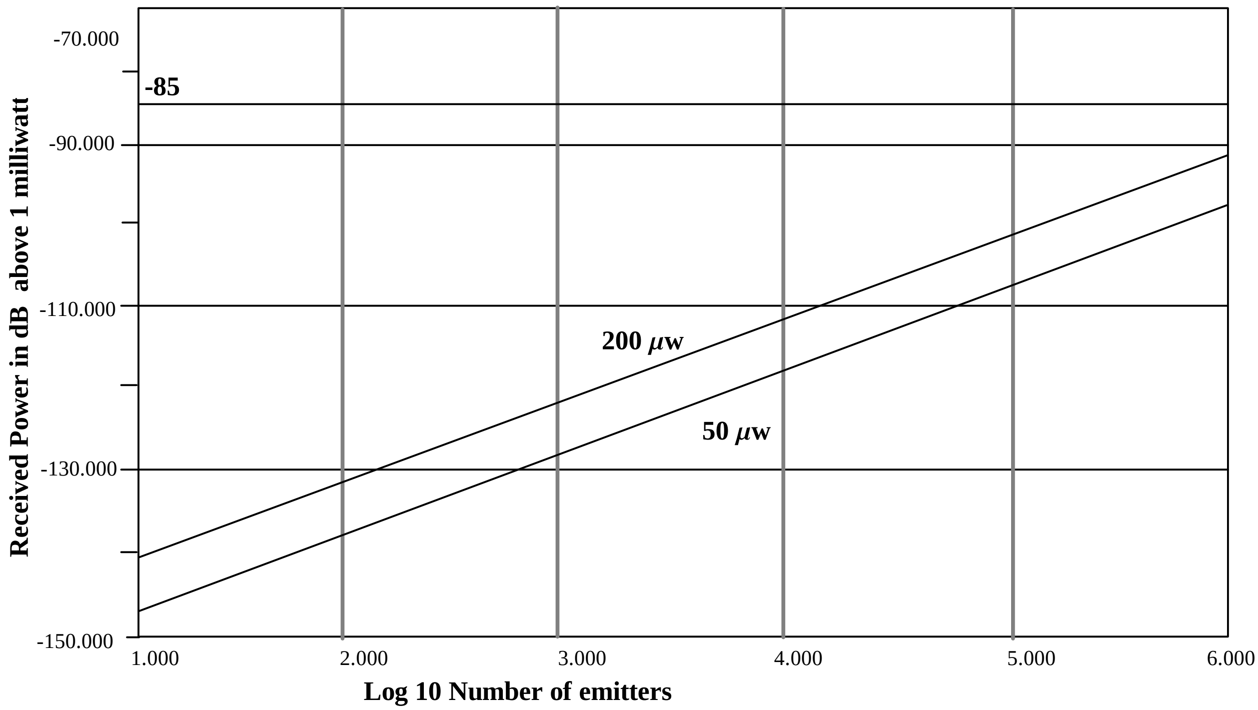

Exhibit 5. Computational results for a DME receiver 300 meters above an open urban environment.

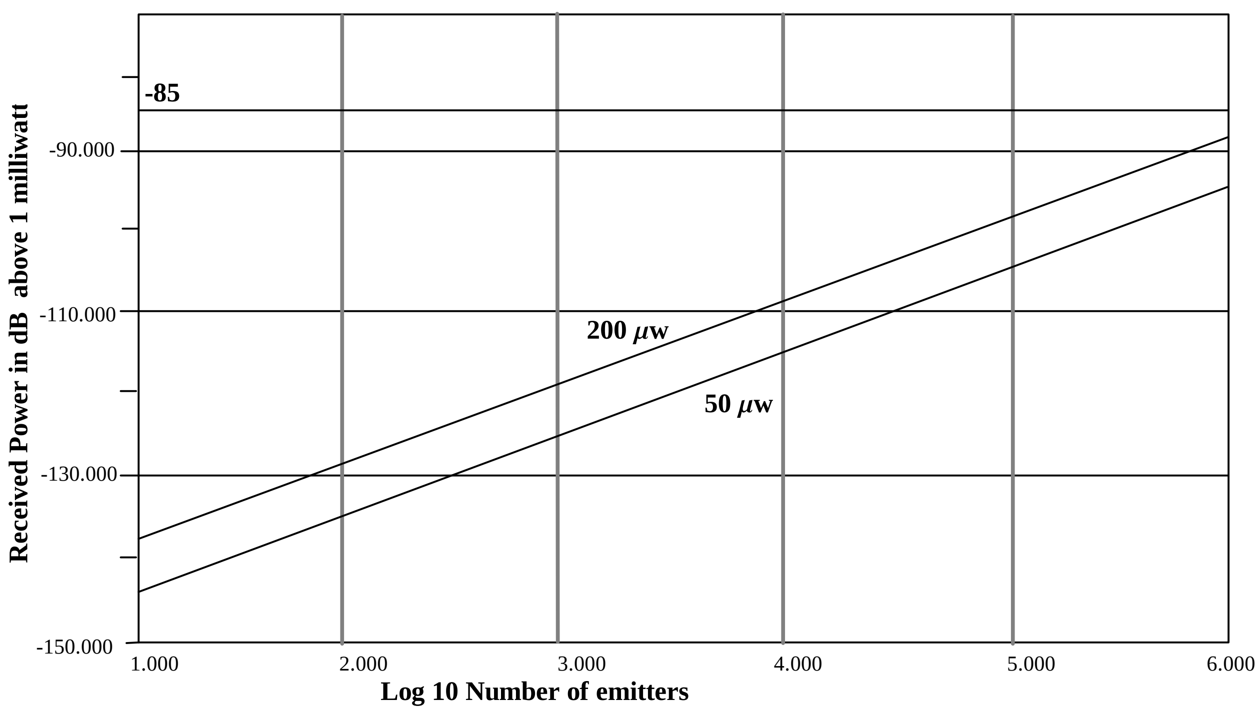

Exhibit 6. Computational results for a DME receiver 300 meters above a 25-story building.

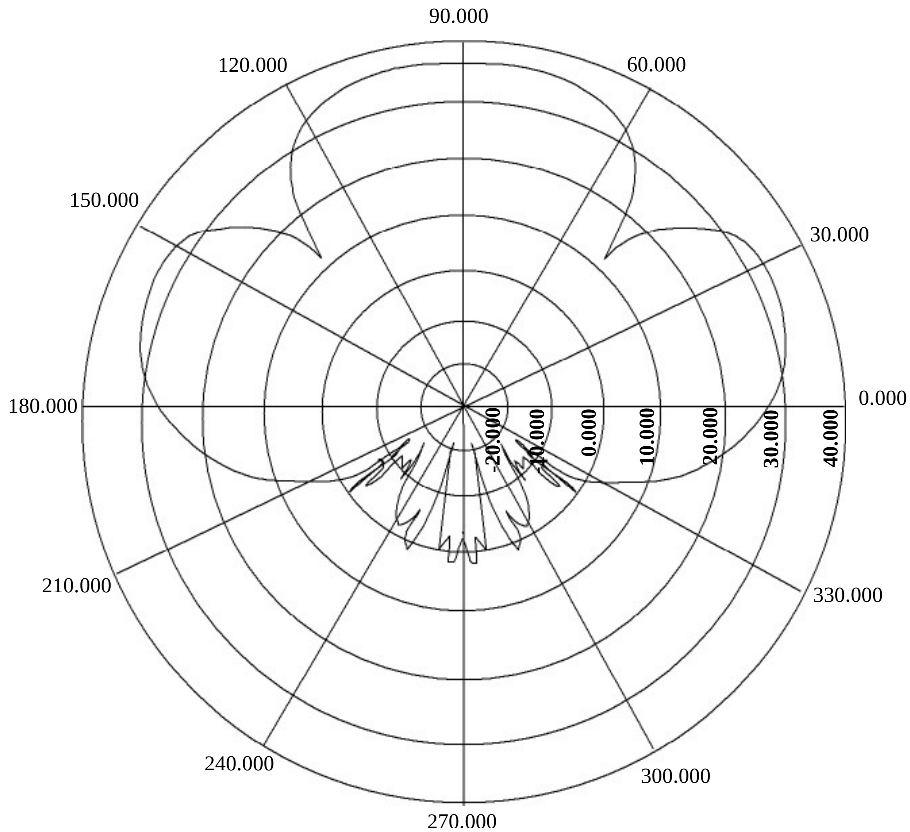

Exhibit 7. Computed radiation pattern for a GPS antenna with center of radiation 0.15 meters (about 6 inches) above a 4-meter diameter fuselage.

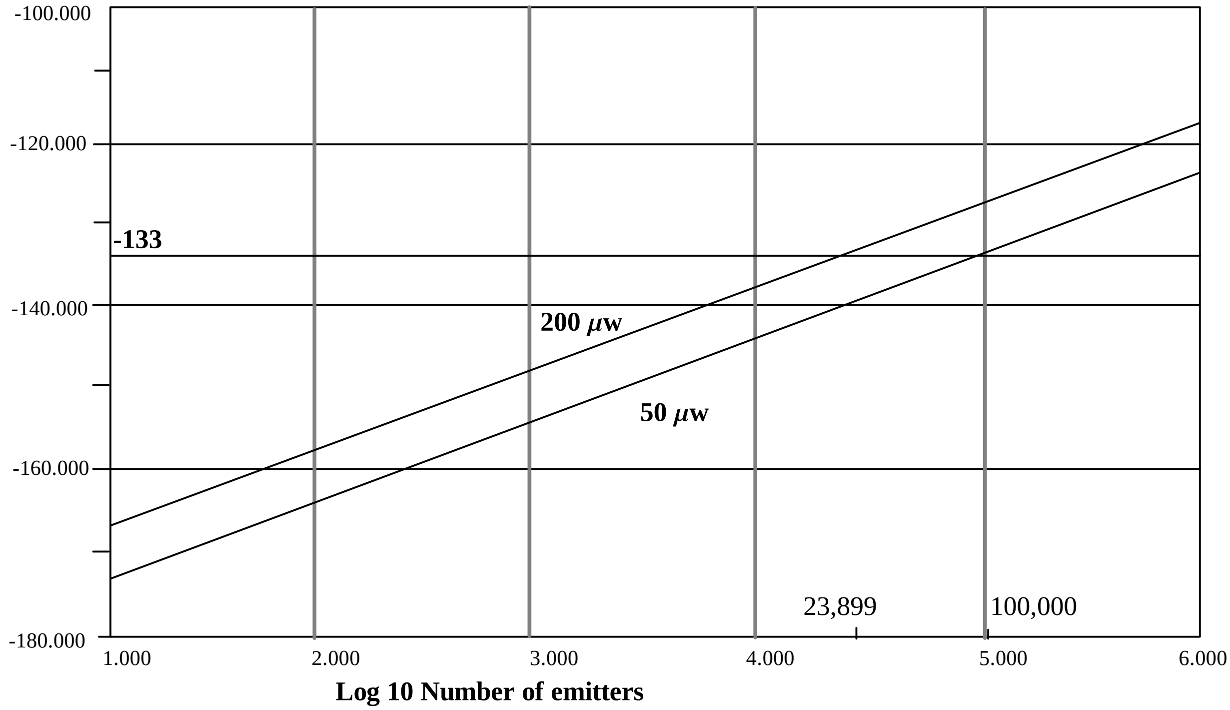

Exhibit 8. Computational results for GPS receiver 300 meters above an open urban environment.

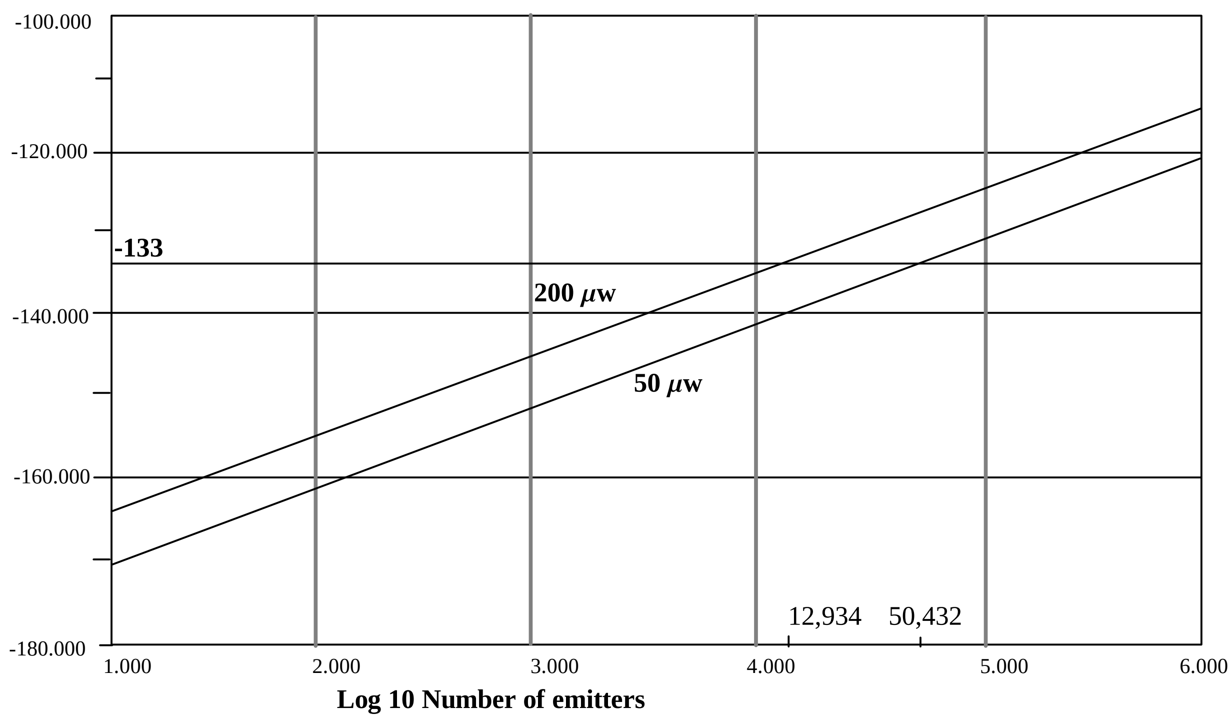

Exhibit 9. Computational results for a GPS receiver 300 meters above a 25-story office building.

Receiver / Emitter Environment	Voice	DME	GPS using C/A Code
Open Urban Area	9,397 36,946	$>10^6$ $>10^6$	23,899 100,000
25 Story Building	5,367 23,899	$>10^6$ $>10^6$	12,434 50,432

Exhibit 10. Number of emitters which may operate simultaneously before total received power equals receiver sensitivity. The top and bottom values corresponding to emitter powers of 200 and 50 microwatts, respectively.

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Attachment A to Appendix B

Cumulative Electromagnetic Radiation from Multiple TDSI Transmitters

written by Dr. Jerry Raines

INTRODUCTION

A previous report (Raines, July 19, 1991) described a general class of waveforms (Gaussian Modulated Carriers) that might be radiated from a TDSI (Time Domain Systems, Inc.) transmitter. These waveforms were designed to fit into regions of the electromagnetic spectrum available according to FCC Part 15 Rules. Assuming that each individual TDSI transmitter complies with those Rules, we still wish to know the cumulative electromagnetic radiation from multiple TDSI transmitters in simultaneous operation. In the present report, we will estimate the amount of that cumulative radiation. In particular, we wish to answer at least two questions. First, what is the absolute amount of power delivered to a non-TDSI (e.g., a television) receiver? Second, how does this amount of power compare with the signal incident from licensed services such as FM radio and television?

In the next section, a mathematical model of electromagnetic radiation from multiple TDSI transmitters is derived. The radiation will appear as noise to non-TDSI receivers. The transmitters are uniformly distributed throughout a cylindrical volume with arbitrary height and diameter. This volume can be used to approximate individual buildings or entire towns and cities.

The model is based upon Okumura's measurements[43] of radio wave propagation at 1920 MHz, and so this report emphasizes one frequency band, centered at 1961 MHz, with bandwidth 476 MHz. This band was identified in the previous report as being available

[43] Okumura, Y. et al, “Field Strength and Its Variability in VHF and UHF Land-Mobile Radio Service”, Review of the Electrical Communications Laboratory, Volume 16, Numbers 9 – 10, September – October, 1968, pgs. 825 – 873.

according to FCC Part 15 Rules. A lower band, with center frequency at 787 MHz and width 344 MHz, is also available for TDSI operation. This band would almost certainly provide greater useable communication range because of its longer wave length. Unfortunately, it partially overlaps the UHF television band. For example, television Channel 38 occupies the band from 614 MHz through 620 MHz. So, that industry would probably vigorously contest its use. The band centered at 1961 MHz is sufficiently far removed from the television and FM radio bands so that those industries would probably not object strongly to its use.

The model was evaluated using a computer program called NOISE. Three different volumes were investigated l) a low, sprawling building such as a factory; 2) a tall building; and 3) an entire urban area. It was found that the cumulative radiation depends upon the density of transmitters (i.e., number of transmitters per unit volume) and the radiated power per transmitter, among other factors.

For interpreting computed results, we will find that a useful benchmark is -60 dBuw (decibels above one microwatt) of cumulative noise power delivered to a non-TDSI receiver. There are at least two reasons for selecting this benchmark. First., it is roughly the same amount of power as that delivered by a Part 15-certified device at a distance of three meters. That is, it is equivalent to an electric field of 500 microvolts per meter incident upon an efficient dipole terminated in a 50-ohm load. Second, -60 dBuw provides 20 dB of protection to a hypothetical FM radio or television broadcast signal. We say "hypothetical" because no such signals are in the 1961 MHz band at the time of this writing. Still, demonstrating such protection is part of a quantitative argument for allowing TDSI transmitters in the 787 MHz band, over the protests of the FM radio and television industries. In a future report this argument could be pursued by performing additional modeling and computations in the 787 MHz band.

In the best case considered, the cumulative radiation model showed that over one-million TDSI transmitters could operate within an urban environment. That is, over one-million transmitters produced a cumulative noise power of -60 dBuw or less. The number of transmitters decreases rapidly, however, if the power per transmitter increases beyond one microwatt and/or the protection for licensed, broadcast signals (i.e., radio and television) increases beyond 20 dB. In the worst case considered for the urban environment, the number of transmitters decreases to only 29. Results were similar for the other two volumes.

DERIVATION OF FORMULAS AND MODEL

Exhibit 1 shows the geometry of interest. A transmitter and receiver are contained in a cylindrical volume of radius b and height 2h. The receiver is located along the axis of the cylinder. Thus, its position expressed in cylindrical coordinates is (O, h_R). The transmitter may be anywhere within the cylinder. Its position is (ρ, z). The straight line distance between the receiver and transmitter is R.

In an urban area, Okumura showed by measurement that radio waves do not propagate as they would in empty space. This is due chiefly to scattering and diffraction by obstacles such as buildings. Exhibit 2 shows his measurements at a frequency of 1920 MHz, which is close to a frequency of interest here. His complete report, including measurements at other frequencies, is contained in Appendix 1. Okumura's measurements suggest the following formula for electric field intensity:

(1) $$E = \frac{K}{r^{3/2}}\sqrt{\frac{h\ P_T g_T}{4p}} \quad volts/meters$$

In equation 1, the factor K is of the form:

(2) $$K = A\left|z - h_R\right| + B \quad meters^{1/2}$$

The constants A and B in equation 2 may be determined using the data in Exhibit 2 together with the method of least-squares. The results are:

(3) $$A = 0.01359 \quad meters^{-1/2}$$

(4) $$B = 0.6009 \quad meters^{1/2}$$

Okumura's measurements begin at a radial distance of 600 meters between transmitter and receiver. At closer distances, we assume that scattering and diffraction do not yet dominate. So, the field intensity may be described by a formula that more closely resembles radio wave propagation in empty space:

(5) $$E = \frac{e^{-a\,R}}{R}\sqrt{\frac{hP_T g_T}{4p}} \quad volts/meter$$

In equation 5, an attenuation constant has been added to account for some scattering and diffraction. Also, the straight line distance between transmitter and receiver is:

(6) $$R = \sqrt{r^2 + (z - h_R)^2}$$

To determine the attenuation constant, we require that equations 1 and 5 be continuous at the radial distance ρ = 600 meters:

(7) $$\frac{K}{r_0^{\ 3/2}}\sqrt{\frac{hP_T g_T}{4p}} = \frac{e^{-a\,R_0}}{R_0}\sqrt{\frac{hP_T g_T}{4p}}$$

In equation 7,

(8) $$r_0 = 600 \quad meters$$

and

(9) $$R_0 = \sqrt{600^2 + (z - h_R)^2}$$

Solving equation 7 for the attenuation constant:

(10) $$a = \frac{1}{R_0}\left(\frac{3}{2}\ln\, r_0 - \ln KR_0\right)$$

With equations 1 and 5, we have a complete description of the electric field radiated from a single transmitter at any distance from the receiver. The power received is:

(11) $$P_R^{'} = \frac{E^2}{h} \quad \frac{g_R\, l^2}{4p} \quad \frac{B_R}{B_T}$$

In equation 11, η is the impedance of free space (about 377 ohms); g_R is the directivity of the receive antenna; and λ is the wavelength. B_R and B_T are the bandwidths of the receiver and transmitter, respectively. In general, they are not the same. For example, the transmitter might be a TDSI type with bandwidth about 1 GHz, while the receiver might be a conventional television tuned to a channel with bandwidth of only 6 MHz.

Of interest here is the power received not from just one transmitter but from a multitude of them, so many, in fact, that their individual positions are practically impossible to enumerate. Therefore, we approximate their positions by distributing them uniformly, such that their density is N transmitters per unit volume, throughout the cylinder. The power received from such a distribution is:

(12) $$P_R = 2p\int_0^b r\, dr \int_{-h}^{h} dz N P_R^{'}$$

Using equations 1, 5, and 11, equation 12 becomes:

(13) $$P_R = 2p\; N\, P_T\, g_T\, g_R \left(\frac{l}{4p}\right)^2 \frac{B_R}{B_T} \int_{-h}^{h} dz\left(I_1 + K^2 I_2\right)$$

In equation 13 the integrals are:

(14) $$I_1 = \int_0^a \frac{e^{-2a\,R}\, r\, dr}{R_2}$$

and:

(15) $$I_2 = \int_a^b \frac{dr}{r^2}$$

In equation 14, the straight line distance R is described by equation 6. In both equations 14 and 15, the limit of integration a is:

(16) $$a = r_0 = 600\, meters$$

The integral I_1 can be evaluated analytically as follows. It is of the form:

(17) $$I_1 = \int_0^a \frac{e^{-2a\sqrt{r^2+b^2}}}{r^2 + b^2} r\, dr$$

where:

(18) $$b = z - h_R$$

Make the change of variable,

(19) $$w = 2a\sqrt{r^2 + b^2}$$

Using equation 19, equation 17 becomes:

(20) $$I_1 = \int_{2ab}^{2a\sqrt{a^2+b^2}} \frac{e^{-w}\, dw}{w}$$

Equation 20 may be evaluated in terms of a well known mathematical function from applied physics, known as the exponential integral. This function is defined as:

(21) $$E_1(x) = \int_c^{\infty} \frac{e^{-t}\, dt}{t}$$

Using equation 21, equation 20 becomes:

(22) $$I_1 = E_1(2a\,|z - h_R|) - E_1\left(2a\sqrt{a^2 + (z - h_R)^2}\right)$$

The second integral I_2 in equation 13 may be evaluated using elementary methods:

$$(23) \quad I_2 = \frac{1}{a} - \frac{1}{b}$$

Using equations 22 and 23, equation 13 becomes:

$$(24) \qquad P_R = 2p\ N\, P_T\, g_T\, g_R \left(\frac{l}{4p}\right)^2 \frac{B_R}{B_T} \quad \ldots$$

$$\left\{ \int_{-h}^{h} dz \left[E_1\left(2a\left|z-h_R\right|\right) - E_1(2a\sqrt{a^2+(z-h_R)^2}\right] + \left(\frac{1}{a}-\frac{1}{b}\right) \int_{-h}^{h} dz K^2 \right\}$$

On the right side of equation 24, the second integral may be evaluated using equation 2:

$$(25) \quad \int_{-h}^{h} dz K^2 = \frac{A^2}{3}\left[\left(h-h_R\right)^3 + \left(h+h_R\right)^3\right)\right] + 2hB^2 + 2AB(h^2+2hh_R-3h_R^2)$$

We have almost completed the mathematical model. Only a couple of finishing touches remain. First, we will express the transmitter density N as:

$$(26) \quad N = \frac{n}{2p\, b^2 h}$$

where n is the total number of transmitters. Second, we will express the wave length in terms of frequency

$$(27) \quad l = \frac{c}{f}$$

Using equations 25 through 27, equations 24 becomes:

$$(28) \quad P_R = \frac{nP_T\, g_T\, g_R B_R}{hB_T} \left(\frac{c}{4p\, b\, f}\right)^2 \ldots$$

$$P\left\{ \int_{-h}^{h} dz \left[E_1\left(2a\left|z-h_R\right|\right) - E_1\left(2a\sqrt{a^2+(z-h_R)}\right)^2 \right] + \left(\frac{1}{a}-\frac{1}{b}\right) \left[\frac{A^2}{3} \quad \left(\left(h-h_R\right)^3 + \left(h+h_R\right)^3\right)\right) + 2hB^2 + 2AB\left(h^2+2hh_R-3h_R^2\right)\right.$$

In equation 28, the integral must be evaluated numerically; however, the integrand is well behaved, and so this is not a problem.

COMPUTATIONAL RESULTS

The mathematical model developed in the preceding section was implemented as a computer program called NOISE. An example plus a complete listing of the program are found at the end of this report.

NOISE was used to evaluate the cumulative electromagnetic radiation from TDSI transmitters, in three different regions. They are shown in Exhibit 3. It is seen that all regions are approximated by cylinders. This keeps the mathematical model relatively simple, as discussed in the preceding section. The dimensions of the cylinders were selected to model a tall building, a long and low building (e.g., a factory), and an urban area. We now examine these evaluations in detail.

Exhibit 4 shows the results, in terms of noise power at the input of a receiver with 6 MHz bandwidth (i.e., a television receiver), for an urban area. Two curves are shown on the same plot. The upper curve was computed by assuming each TDSI transmitter radiates 1 milliwatt time-average power. The lower curve assumes microwatt time-average power. At the time of this writing, the exact time-average power is not known; however, it probably is between these two bounds. In both cases, the center frequency was 1961 MHz, and the bandwidth was 476 MHz. In general, if the receiver bandwidth decreases and/or the transmitter bandwidth increases, then the curves will shift downward. That is, the cumulative noise will decrease. Exhibit 5 shows the results for the factory. The cumulative noise definitely has increased compared with the urban area. This is as expected because the transmitters are contained in a much smaller volume.

Exhibit 6 shows cumulative noise in a tall building. It has increased slightly compared with the factory, even though the volume has actually increased. This indicates that shape is a factor as well as volume.

Exhibit 7 provides perspective to the results in Exhibits 4 through 6. In the second column are the field intensities of broadcast services (e.g., FM radio and television) which are protected from interference by the FCC. Also shown is the field intensity of a FCC Part 15-certified device at a distance of three meters. To compare these field intensities with the cumulative noise plotted in Exhibits 4 through 6, we will need a formula to convert from units of dBu (decibels above one microvolt per meter) to units of dBuw (decibels above one microwatt). The formula may be derived as follows. We begin with the fundamental communications equation,

(29) $$P_R = \frac{E^2}{h} \quad \frac{l^2 g_R E_R}{4p}$$

In equation 29, the symbols used are the same as in the preceding section. Using equation 27 to convert from wavelength to frequency, equation 29 becomes:

(30) $$P_R = \frac{E^2}{h} \quad \frac{c^2}{4p} \quad \frac{g_R E_R}{f^2}$$

Assume that the receiving antenna is an efficient dipole:

(31) $$g_R E_R = 3/2$$

Next, express the received power P_R in units of microwatts P_{uw}:

(32) $$P_R = P_{uw}\ x10^{-6}$$

Similarly, express the incident field intensity E in units of microvolts per meter E_u

(33) $$E = E_u\ x\,10^{-6}$$

Finally, express the frequency f in units of MHz,:

(34) $$f = MHz\ x\,10^{-6}$$

Using equations 31 through 34, equation 30 becomes:

(35) $$P_{uw} = \left(\frac{E_u}{MHz}\right)^2 \frac{3c^2\ x\,10^{-18}}{8ph}$$

Taking ten times the logarithm of both sides of equation 35, obtain:

(36) $$10\log P_{uw} = 20\log E_u - 20\log(MHz) - 45.45$$

Finally, define:

(37) $$P_{dBw} = 10\log P_{uw}$$

and:

(38) $$E_{dBu} = 20\log E_u$$

Using equations 37 and 38, equation 36 becomes:

(39) $$P_{dBuw} = E_{dBu} - 20\log(MHz) - 45.45$$

Equation 39 is the desired transformation formula. The results of using the formula are shown in the fourth column of Exhibit 7. These may be compared directly with the results in the exhibits 4 through G, which are in the same units (dBuw).

From Exhibit 7, it is seen that the broadcast services deliver as little as -40 dBuw (i.e., one-ten-thousandth of a microwatt) to receivers. That signal, if it were in the same band as the TDSI transmitter, would have to be protected. The FCC would prefer about 40 dB (i.e., a factor of 100 in field intensity) of protection. This assumes the interfering signal could be intelligible to the receiver, however. Actually, the broadcast probably could co-exist with a noise-like signal from TDSI using even less protection, say 20 dB (a factor of 10 in field intensity).

In view of the above paragraph, a desirable cumulative noise would likely be either -60 dBuw or -80 dBuw, depending upon how much protection the broadcast services actually require from noise-like signals. Exhibit 8 shows how many transmitters could be allowed in a region and still provide that much protection. It is seen that the number depends greatly upon the Output power per transmitter, which is as expected. The best case is a one-microwatt transmitter in an urban area. If only 20 dB of protection is desired (i.e., -60 dBuw noise power), then over 1 million transmitters could be deployed. The worst cases are clearly one-milliwatt transmitters in tall buildings and factories. None are allowable.

The results in Exhibit 8 lead naturally to another calculation. That is the volume allowed to each transmitter, assuming they are uniformly distributed over the region. Such a volume is shown in Exhibit 9, in the form of a cube. Exhibit 10 shows the dimensions of the cube in the various cases considered. It is seen that the results are consistent: For a 1 microwatt transmitter providing 20 dB of protection, the cube must be on the order of 10 meters per side. The variation from case to case is due to the precise shape of the region.

Note that all computations assumed that the receiver is in the center of the region. Thus, at least one practical question remains answered. That is, how much cumulative noise is radiated outside the region containing the transmitters? For example, would a tall building packed with TDSI transmitters cause perceptible interference to broadcast receivers outside of the building? Certainly, as we have seen here, there would be interference inside the building, but perhaps no one would object.

CONCLUSIONS

A mathematical model has been derived for the cumulative electromagnetic radiation from multiple TDSI transmitters. The model includes the effects of design parameters such as frequency, bandwidth, antenna directivity, and power. It also shows the effects of the dimensions of the environment and the bandwidth of the affected receiver.

The model has been implemented as a computer program called NOISE. The program was exercised for three representative environments: a low, sprawling, factory-type building; a tall office-type building; and an entire urban area. It was assumed that the receiver was in the center of the region and that it had a bandwidth of 6 MHz, similar to that of a television receiver. The transmitters operated in a region of the spectrum presently available according to FCC Part 15 Rules, with a bandwidth of 476 MHz, centered about 1961 MHz.

For comparison with the results from our model, some sort of benchmark was required. This was a challenge in the 1961 MHz band. There are no licensed services such as FM radio and television broadcasts, and, therefore, no requirements to protect such signals which might be used as benchmarks. To provide perspective to our results, therefore, we arbitrarily introduced all benchmark of -60 dBuw (decibels above one microwatt) of power received by a non-TDSI receiver.

The above benchmark has at least two mearlingfu1 interpretations. First, it is roughly (within 3 dB) the power delivered by a single Part 15-certified device at a distance of three meters. Thus, if the noise power received from multiple devices is no rnore than -60 dBuw, then they cumulatively interfere no more than a single Part 15-certified device. Second, -60 dBuw provides at least 20 dB of protection to hypothetical FM radio and television signals in that band. Thus, multiple devices delivering no more than -60 dBuw to a receiver would not be expected to interfere with licensed broadcast signals. Such devices could coexist with licensed signals in the 787 MHz band, where radio wave propagation provides superior communication range. In fact, that band is available according to Part 15 Rules; however, the FM radio and television industries would almost certainly voice strong opposition. The above argument concerning coexistence might be used against such opposition.

Using the above benchmark, the computed results emphasize the relationship between two parameters, the density of the transmitters (i.e., the number of transmitters per unit volume of the environment); and the power radiated per transmitter. For example, if the latter is one microwatt or less, then over million TDSI transmitters could operate within an urban environment. Note that this result assumes that the transmitters are uniformly distributed throughout the environment.

Results are similar for the other two environments. In a factory-type building, if the radiated power is one microwatt or less, and using the benchmark of -60 dBuw, then the model shows that 89 TDSI transmitters could operate. In a tall, office-type building, 35 transmitters are allowed. Though these absolute numbers of transmitters are far less than the one-million-plus for an entire urban area, the transmitter densities are roughly the same, on the order of one transmitter per thousand cubic meters.

If the power per transmitter increases, or; if the benchmark becomes more restrictive, then the number of allowable transmitters decreases drastically. For example, in the urban area, if the power increases from one microwatt to one milliwatt, then the number of transmitters decreases from over one million to about four thousand. If, in addition, the benchmark decreases from -60 dBuw to -80 dBuw (corresponding to increasing protection for licensed services from 20 dB to 40 dB), then the number of transmitters decreases further to only 29.

The above results show that multiple TDSI transmitters can operate in the 1961 MHz band. Further, they suggest that multiple TDSI transmitters could coexist with licensed broadcast services in the 787 MHz band, where radio wave propagation is more favorable. In a future report, this conclusion could be further explored by exercising the model in that band.

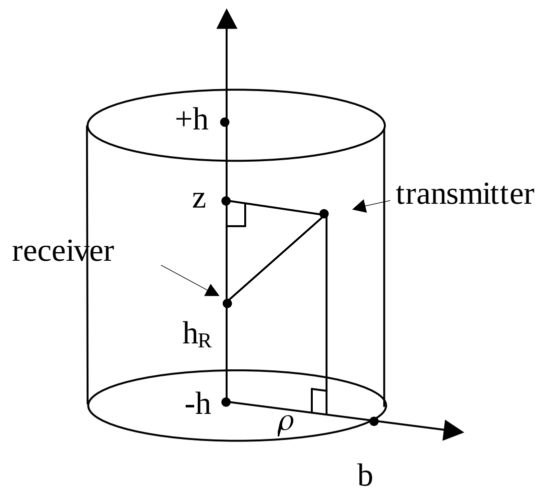


Exhibit 1. Geometry for mathematical model of cumulative radiation.

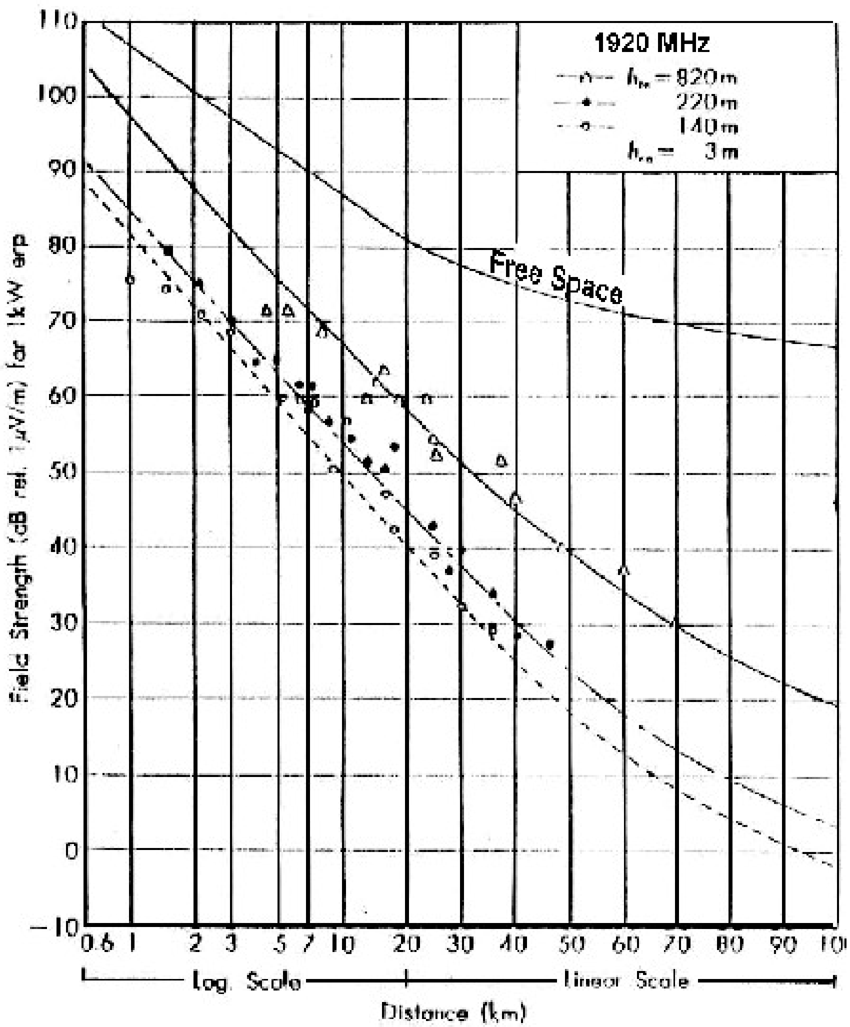


Exhibit 2. Radio wave propagation measurements by Okumura, at a frequency of 1920 MHz.

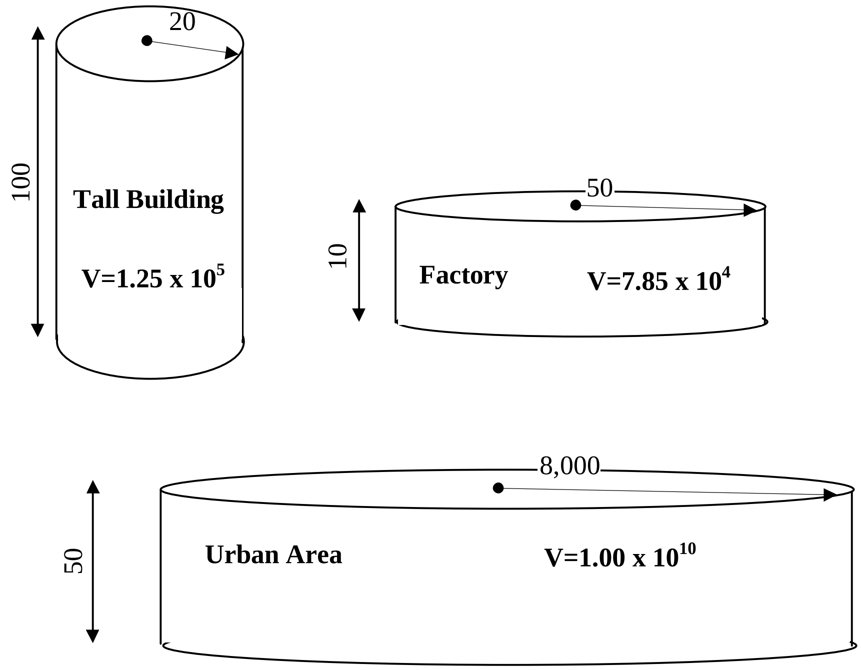


Exhibit 3. Typical regions containing TDSI transmitters. Cylindrial models are used for mathematical simplicity. Dimensions are in meters. Volumes are in cubic meters.

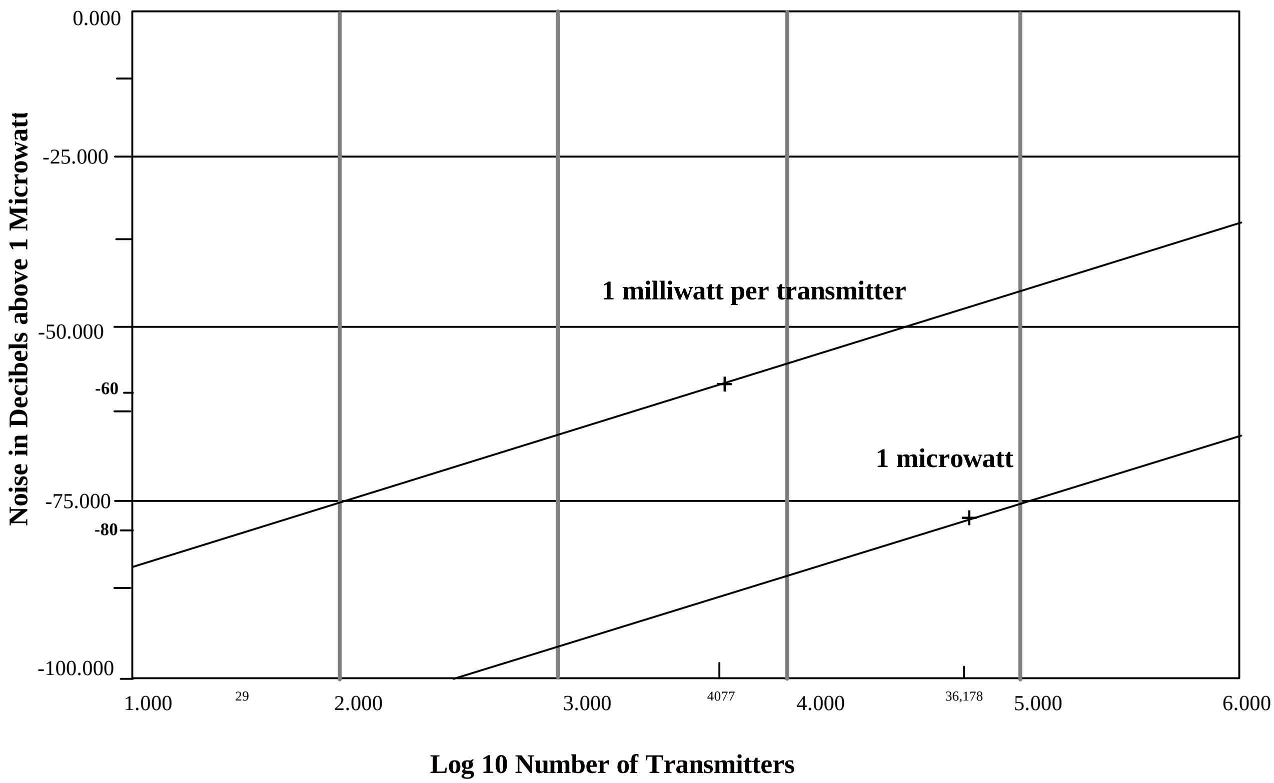


Exhibit 4. Cumulative noise in an urban area as a function of number of transmitters (10 through 1 million). The two different curves correspond to different radiated powers per transmitter.

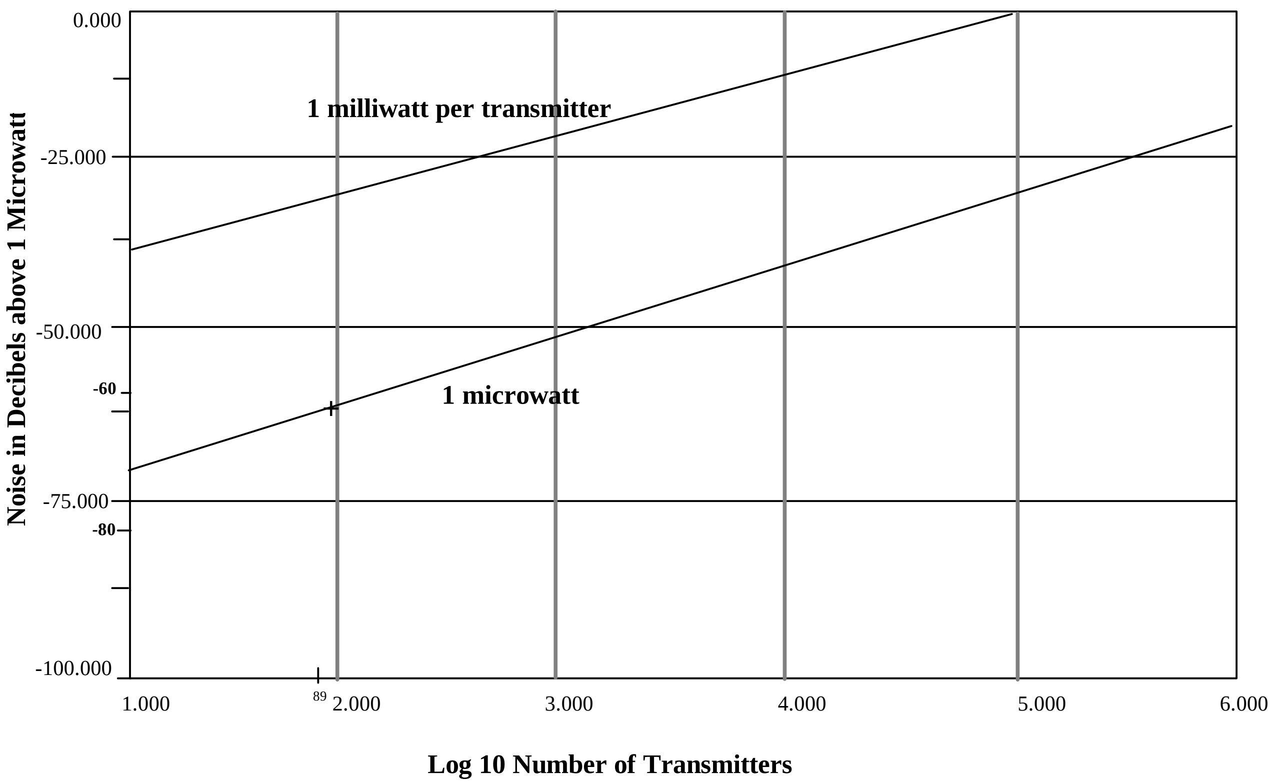


Exhibit 5. Cumulative noise assuming all transmitters are contained within a factory type building.

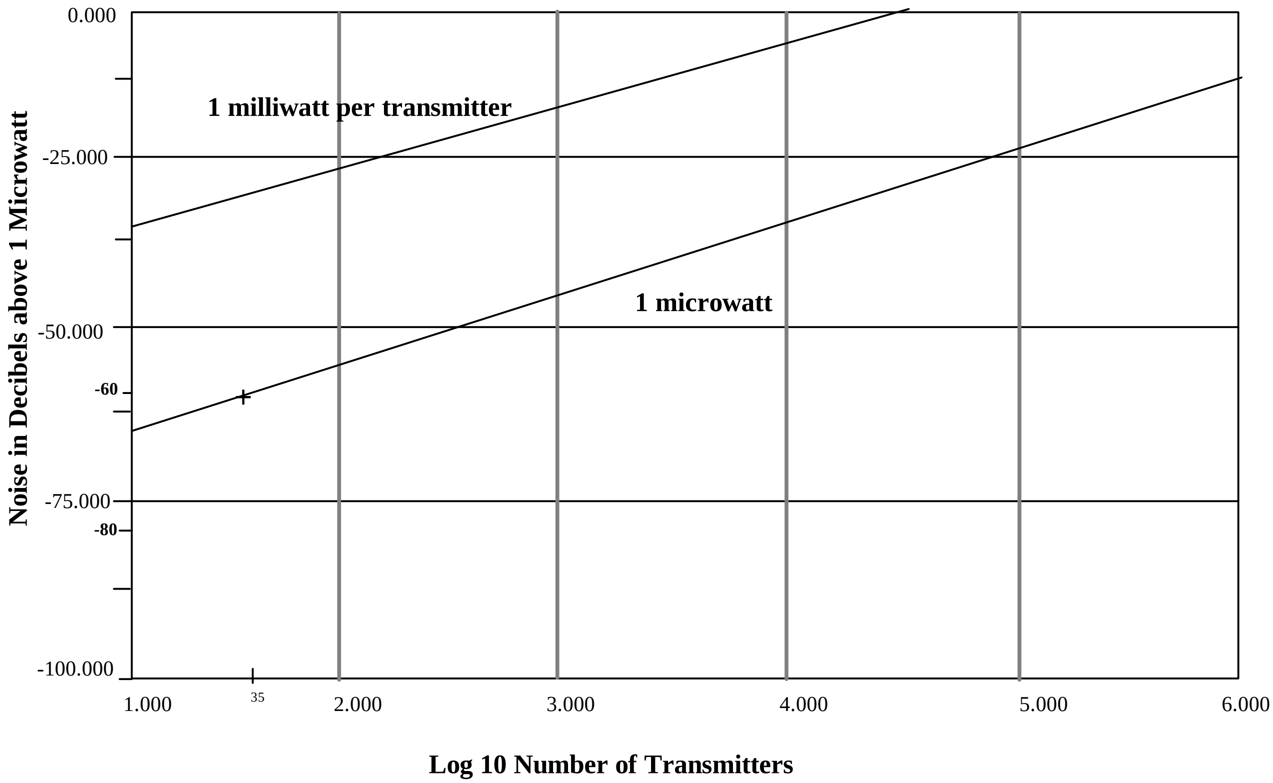


Exhibit 6. Cumulative noise assuming all transmitters are contained within a tall building.

Service	Protected field intensity in dB above 1 microvolt/meter (dBu)	Frequency in MHz	Received power in dB above 1 microwatt (dBuw)
FM	60	100	-25.45
VHF-lo	47	88	-37.34
VHF-hi	56	216	-36.14
UHF	64	776	-39.25
Part 15 at 3 meters	54	1961	-57.30

Exhibit 7. Field intensities (in dBu) and corresponding received power (indBuw) for various licensed broadcast services. These signals must be protected according to FCC rules.

	1 milliwatt per transmitter		**1 microwatt per transmitter**	
Cumulative noise / Region	**-60**	**-80**	**-60**	**-80**
Urban Area	**4,077**	**29**	**>1,000,000**	**36,178**
Factory	**0**	**0**	**89**	**0**
Tall Building	**0**	**0**	**35**	**0**

Exhibit 8. Number of allowable transmitters, assuming either 1 milliwatt or 1 microwatt of power radiating from each, and assuming either 20 dB (-60 dBuw) or 40 dB (-80 dBuw) of protection for licensed services.

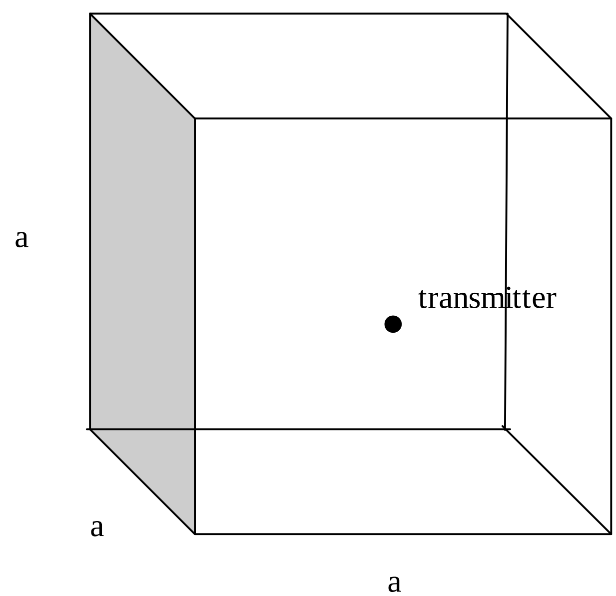


Exhibit 9. If transmitters are uniformly distributed within a region, then each may be assumed at the center of a cube.

	1 milliwatt per transmitter		1 microwatt per transmitter	
Cumulative noise / Region	-60	-80	-60	-80
Urban Area	135	701	21.5	65.2
Factory	∞	∞	9.7	∞
Tall Building	∞	∞	15.3	∞

Exhibit 10. Dimension of cube surrounding each allowed transmitter, for various assumed radiated powers and degrees of protection for licensed broadcast services.

Computer Program "Noise"

```
CUM NOISE
CUMULATIVE NOISE OF INCOHERENT EMITTERS VERSION 1.0
DESIGN PARAMETERS ARE:
        1 - LOG10 (NUMBER OF EMITTERS):     0
        2 – LOG10 (POWER PER EMITTER IN WATTS):     0
        3 – FREQUENCY IN MHZ:       1961
        4 – BANDWIDTH OF EMITTERS IN MHZ: 160
        5 - DIRECTIVITY OF TRANSMIT ANTENNA, NOT IN DB: 1.5
        6 – BANDWIDTH OF RECEIVERS IN MHZ: 6
        7 – DIRECTIVITY OF RECEIVE ANTENNA, NOT IN DB: 1.5
        8 – HEIGHT OF RECEIVE ANTENNA IN METERS: 50
        9 – RADIUS OF MARKET IN METERS: 10
  10 – HEIGHT OF MARKET IN METERS: 100
  11 – DISTANCE FROM RECEIVER TO NEAREST TRANSMITTER IN METERS: 0
CONTINUOUSLY VARIED DESIGN PARAMETER?  (INTEGER 1-11)  1
START, STOP, STEP: 1,6.1, .1
DISCRETELY VARIED DESIGN PARAMETER?  (INTEGER 1-11)  2
START, STOP, STEP:  -6, -3, 3
NAME OF OUTPUT FILE: DLZ: NOISE.OUT
COLUMNS IN OUTPUT FILE ARE:
        1 – CONTINUOUSLY VARIED DESIGN PARAMETER
        2 – NOISE IN DBUW FOR DISCRETE PARAMETER VALUE  -0.60000000E+01
        3 – NOISE IN DBUW FOR DISCRETE PARAMETER VALUE  -0.30000000E+01
STOP - -
```

```
NOISE.FOR
C
C  CUMULATIVE NOISE OF INCOHERENT TRANSMITTERS
C
                PROGRAM NOISE
                DIMENSION DV (11), QVAR (10), FILNAM (4)
                DATA ETA, PI  /376.73035, 3.141592654/
                WRITE (5, 100)
100     FORMAT (//, 1X, 'CUMULATIVE NOISE OF INCOHERENT EMITTERS',
        1' VERSION 1.0', //,
        11X, 'DESIGN PARAMETERS ARE: ',/,
        15X, '1 – LOG10 (NUMBER OF EMITTERS): ', $)
        READ  (5,*)  DV (1)
        WRITE  (5,200)
200     FORMAT  (5X, '2 – LOG10 (POWER PER EMITTER IN WATTS): ',$)
        READ (5,*)  DV (2)
        WRITE (5,620)
620     FORMAT  (5X, '3 – FREQUENCY IN MHZ: ',$)
        READ (5,*)  DV (3)
        WRITE (5, 300)
300     FORMAT (5X, '4 – BANDWIDTH OF EMITTERS IN MHZ: ',$)
        READ (5,*)  DV (4)
        WRITE (5, 310)
310     FORMAT (5X, '5 – DIRECTIVITY OF TRANSMIT ANTENNA, NOT IN DB: ',$)
        READ (5,*)  DV (5)
        WRITE (5, 400)
400     FORMAT (5X, '6 – BANDWIDTH OF RECEIVERS IN MHZ: ',$)
        READ (5,*)  DV (6)
        WRITE (5, 410)
410     FORMAT (5X, '7 – DIRECTIVITY OF RECEIVE ANTENNA, NOT IN DB: ',$)
        READ (5,*)  DV (7)
        WRITE (5, 610)
610     FORMAT (5X, '8 – HEIGHT OF RECEIVE ANTENNA IN METERS: ', $)
        READ (5,*)  DV (8)
        WRITE (5, 500)
500     FORMAT (5X, '9 – RADIUS OF MARKET IN METERS: ', $)
        READ (5,*)  DV (9)
```

```
      WRITE (5, 600)
600   FORMAT (4X, '10 – HEIGHT OF MARKET IN METERS: ',$)
      READ (5, *) DV (10)
      WRITE (5, 605)
605   FORMAT (4X, '11 – DISTANCE FROM RECEIVER TO NEAREST TRANSMITTER',
      1' IN METERS: ',$)
      READ (5,*)  DV(11)
      WRITE (5, 700)
700   FORMAT (/, 1X, 'CONTINUOUSLY VARIED DESIGN PARAMETER?',
      1' (INTEGER 1-11)  ',$)
      READ (5,*)  IVARY
      WRITE (5, 800)
800   FORMAT (1X, 'START, STOP, STEP: ',$)
      READ (5,*)  PSTART, PSTOP, PSTEP
      WRITE (5, 900)
900   FORMAT (/, 1X, 'DISCRETELY VARIED DESIGN PARAMETER?',
      1'  (INTEGER 1-11)  ',$)
      READ  (5,*)  JVARY
      WRITE  (5, 800)
      READ  (5,*) QSTART, GSTOP, QSTEP
      WRITE  (5, 950)
950   FORMAT (/, 1X, 'NAME OF OUTPUT FILE:  ',$)
      READ (5, 970)  (FILNAM (L), L = 1,4)
970   FORMAT (4A4)
C               WRITE (5, 980)
C980    FORMAT (/1X, ' INTEGRATION STEP SIZE IN METERS: ',$)
C               READ (5,*)  DZ
                NQ = (QSTOP-QSTART) /QSTEP+1.5
                DV (IVARY) + PSTART
                OPEN (UNIT=9, NAME=FILNAM, TYPE='NEW')
1000  CONTINUE
      DO 1100 M=1,NQ
      DV (JVARY)=QSTART+(M-1)*QSTEP
      EMTTRS=1.
      PT=1.
      IF (ABS (DV(1)).GE.1.E-3)  EMTTRS=10.**DV(1)
      IF (ABS (DV(2)).GE.1.E-3)  PT=10.**DV(2)
      GT=DV (5)
      GR=DV (7)
      FREQ=DV (3)*1.E6
      BR=DV (6)*1.E6
      BT=DV (4)*1.E6
      HR=DV (8)
      H=DV (10) /2.
      RAD=DV (9)
      VOLUME=2.*PI*RAD*RAD*H
      TDEN=EMTTRS/VOLUME
      DELTA=DV (11)
      T1=PR (TDEN,PT,GT,GR,FREQ,BR,BT,H,HR,RAD,DELTA)
C               T1=PR (TDEN,PT,GT,GR,FREQ,BR,BT,H,HR,RAD,DZ)
                QVAR (M)=10*ALOG10 (T1)+60.
1100  CONTINUE
      WRITE  (9,1200) DV (IVARY), (QVAR (L),L=1,NQ)
1200  FORMAT  (11(1X,E15.8))
      DV (IVARY)=DV (IVARY)+PSTEP
      IF  (DV (IVARY).LE.PSTOP)  GO TO 1000
      CLOSE  (UNITS=9)
      WRITE  (5,1300)
1300  FORMAT (/,1X,'COLUMNS IN OUTPUT FILE ARE: ',/,
      15X,'1 – CONTINUOUSLY VARIED DESIGN PARAMETER')
      DO 1500 M=1,NQ
      N=M+1
      DV (JVARY)=QSTART+(M-1)*QSTEP
      WRITE (5,1400) N,DV (JVARY)
1400  FORMAT (4X,I2,' – NOISE IN DBUW',
      1' FOR DISCRETE PARAMETER VLAUE ',E15.8)
```

```
1500    CONTINUE
        STOP
        END
C

C  MODEL OF RECEIVED NOISE POWER
C
                FUNCTION PR(TDEN,PT,GT,GR,FREQ,BR,BT,H,HR,RAD,DELTA)
C               FUNCTION PR(TDEN,PT,GT,GR,FREQ,BR,BT,H,HR,RAD,DZ)
                DATA A,B,C,RHO0,PI /.01359,.6009,3.E8,600.,3.141592654/
C
C  TDEN = TRANSMITTER DENSITY (UNITS PER CUBIC METER)
C  PT = RADIATED POWER PER UNIT IN WATTS
C  GT = DIRECTIVITY OF TRANSMIT ANTENA, NOT IN DB
C  GR = DIRECTIVITY OF RECEIVE ANTENNA, NOT IN DB
C  FREQ = FREQUENCY IN HERTZ
C  BR = BANDWIDTH OF RECEIVER IN HERTZ
C  BT = BANDWIDTH OF TRAMSMITTERS IN HERTZ
C  2*H = HEIGHT OF MARKET IN METERS
C  HR = HEIGHT OF RECEIVER IN METERS
C  RAD = RADIUS OF MARKET IN METERS
C  DELTA = DISTANCE BETWEEN RECEIVER AND NEAREST TRANSMITTER
C
C  OUTPUT IS RECEIVED NOISE POWER IN WATTS
C
                DZ=.02*H
                PR=0.
                IF (RAD.LE.RHO0) GO TO 100
                T1=H*H+2.*H*HR-3.*HR*HR
                T2=(H-HR)**3+(H+HR)**3
                T3=A*A/3.*T2+2.*H*B*B+2.*A*B*T1
                PR=T3*(1./RHO0-1./RAD)
                PR=PR-SINT(H,HR,DZ,RHO0)
100     CONTINUE
        IF (DELTA.EQ.0.)  PR=PR+FINT(H,HR,DZ)
        IF (DELTA.GT.0.)  PR=PR+SINT(H,HR,DZ,DELTA)
        T4=TDEN*PT*GT*GR*C*C*BR
        T5=8.*PI*FREQ*BT*FREQ
        PR=PR*T4/T5
        RETURN
        END
C
C  FIRST INTEGRAL IN NOISE MODEL
C
                FUNCTION FINT (H,HR,DZ)
                EXTERNAL ZFUN1
                COMPLEX ZFUN1,C1
                C1=ZINT (ZFUN1,-H,HR-DZ,DZ)
                FINT=REAL (C1)
                C1=ZINT (ZFUN1, HR+DZ,H,DZ)
                FINT=FINT+REAL (C1)
                T1=4.8163+ALOG (DZ)
                T1=2*DZ*T1
                FINT=FINT+T1
                RETURN
                END
C
                FUNCTION ZFUN1 (Z,HR)
                COMPLEX ZFUN1,E1,C1
                T1=ABS (Z-HR)
                T1=2*T1*ALPHA (Z,HR)
                C1=CMPLX (T1,0.)
                ZFUN1=E1 (C1)
                RETURN
                END
C
```

```
C       SECOND INTEGRAL IN NOISE MODEL
C
              FUNCTION SINT (H,HR,DZ,YYY)
              EXTERNAL ZFUN2
              COMPLEX ZFUN2,C1
              COMMON /PARAM/ XXX
              XXX=YYY
              C1=ZINT (ZUN2,-H,H,DZ)
              SINT=REAL (C1)
              RETURN
              END
C
              FUNCTION ZFUN2 (Z,HR)
              COMPLEX ZFUN2, E1, C1
              COMMON /PARAM/ XXX
C             DATA RHO0 /600./
              T1=Z-HR
C             T1=SQRT (RHO0*RHO0+T1*T1)
              T1=SQRT (XXX*XXX+T1*T1)
              T1=2*T1*ALPHA (Z,HR)
              C1=CMPLX (T1,0.)
              ZFUN2=E1(C1)
              RETURN
              END
C
C       NOISE MODEL ATTENUATION CONSTANT
C
              FUNCTION ALPHA (Z,HR)
              REAL K,LOGRHO
              DATA RHO0,A,B, /600., .01359, .6009/
              DATA LOGRHO, RHOSQ / 6.396929655, 3.6E5/
C
C Z = HEIGHT OF TRANSMIT ANTENNA
C HR = HEIGHT OF RECEIVE ANTENNA
C
              T1=Z-HR
              K=A*ABS (T1)+B
              R0=SQRT (RHOSQ+T1*T1)
              ALPHA=1.5*LOGRHO-ALOG (K*R0)
              ALPHA=ALPHA /R0
              RETURN
              END

C
C  FIRST – ORDER EXPONENTIAL INTEGRAL
C
              FUNCTION E1 (Z)
              COMPLEX E1, Z, C1, SUM
              DATA ZBIG, TOL, EUL /8., 1.E-6, .5772156649/
              DATA MSTOP /8/
              IF (CABS (Z).GE.ZBIG)  GO TO 200
              M=1
              C1=-Z
              SUM=C1
100     CONTINUE
        M=M+1
        T1=M
        C1=-Z* (T1-1) / (T1*T1)*C1
        SUM=SUM+C1
        IF (CABS(C1) .GT.TOL)  GO TO 100
        E1=-EUL-CLOG (Z) – SUM
        RETURN
200     CONTINUE
        M=0
        C1=1.
        SUM=C1
```

```
300     CONTINUE
        M=M+1
        T1=M
        C1= -T1 /Z*C1
        SUM=SUM+C1
        IF (M.LE.MSTOP.AND.CABS (C1) .GE.1.E-6)  GO TO 300
        E1=CEXP (-Z) /Z*SUM
        RETURN
        END
C
C  TRAPEZOIDAL INTEGRATION OF COMPLEX FUNCTION
C
                FUNCTION ZINT (ZFUN,A,B,DX)
                COMPLEX ZINT, ZFUN, Z1, Z2, ZAV
C
C  ZFUN = FUNCTIN TO BE INTEGRATED (COMPLEX)
C  A = LOWER LIMIT OF INTEGRATION (REAL NUMBER)
C  B = UPPER LIMIT OF INTEGRATION (REAL NUMBER)
C  DX = STEP SIZE OF INTEGRATION (REAL NUMBER)
C
C  NOTE: ZFUN MUST BE DECLARED EXTERNAL IN CALLING PROGRAM.
C               EXAMPLE:                EXTERNAL ZFUN
C               COMPLEX ZFUN
C
                ZINT=0.
                X1=A
                Z1=ZFUN (X1)
100     CONTINUE
        X2=X1+DX
        IF (X2.GT.B)  X2=B
        Z2=ZFUN (X2)
        DELTAX=X2-X1
        ZAV= .5*(Z1+Z2)
        ZINT=ZINT+ZAV*DELTAX
        X1=X2
        Z1=Z2
        IF (X2.LT.B)  GO TO 100
        RETURN
        END
```

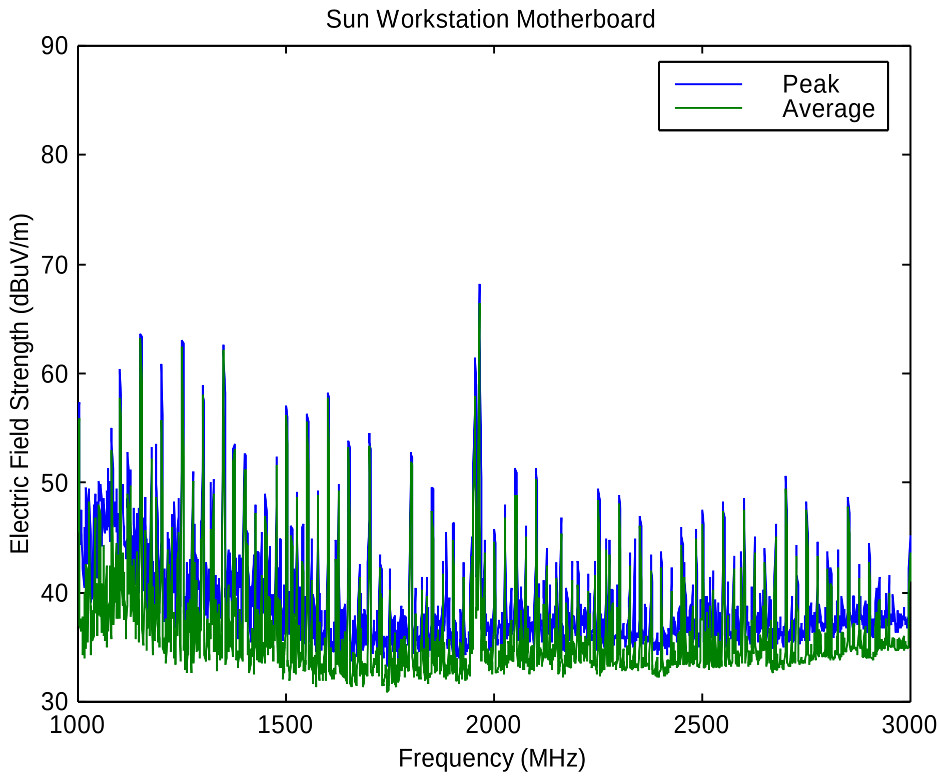
Appendix C

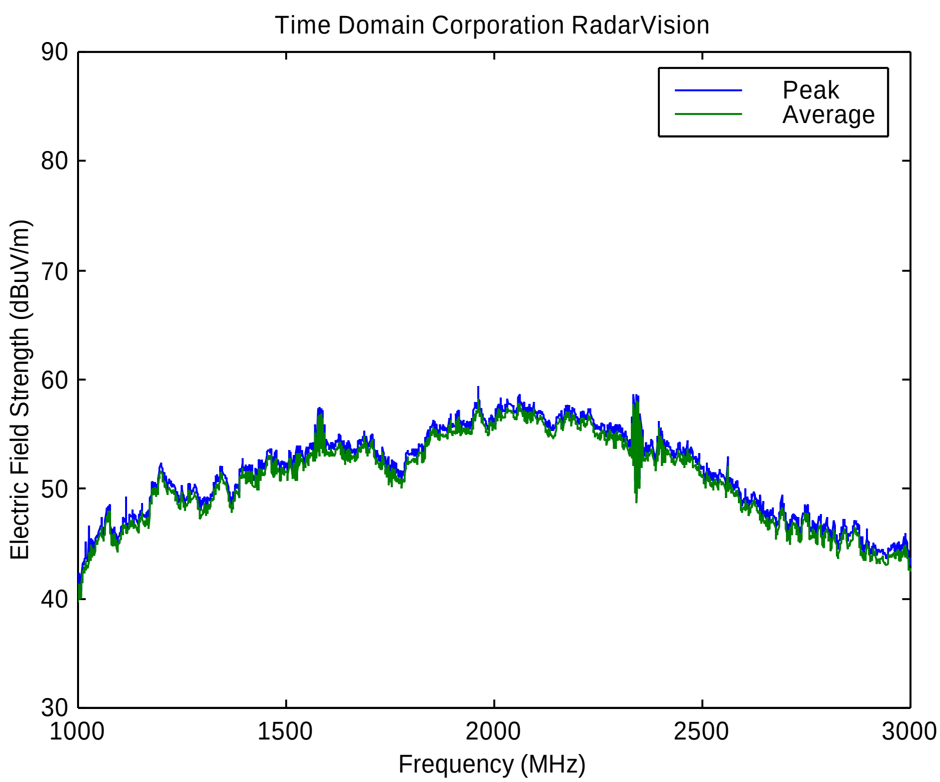
Example UWB Emissions from Incidental, Unintentional, and Intentional Devices

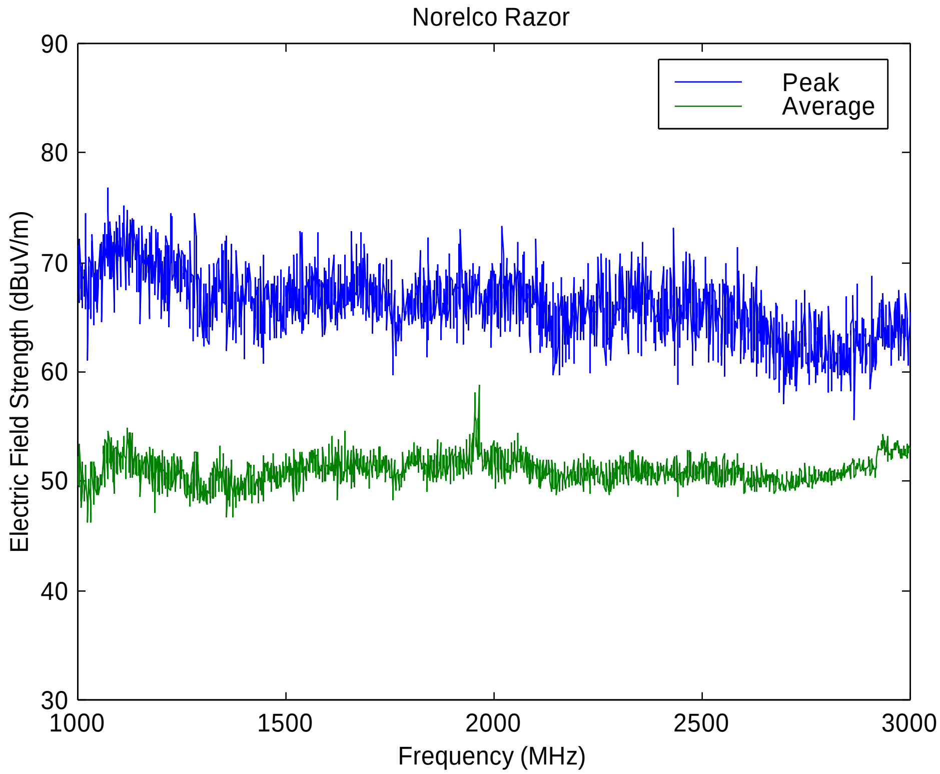
Four plots are shown below. These represent emissions from UWB emitters of all "intent". The Sun Workstation Motherboard represents the emissions from certain digital devices. The incidental radiators are represented by the Norelco razor and CONAIR hairdryer. The UWB "intentional" emissions are from a Time Domain Corporation radar.

All measurements were taken using the standard configuration for emissions above 1 GHz.[44] However, the measurement distance was 1 meter rather than 3 meters to improve the system's signal to noise ratio (common practice for measurements above 2 GHz), and the antenna factors used were for 1 meter. The plots show both the peak and average measurements. Note that the plots also contain the ambient emissions, such as, PCS emissions. A complete study of UWB emissions from incidental radiators was filed September 11, 1998, as an Ex Parte Presentation on the Time Domain Corporation Waiver Request.

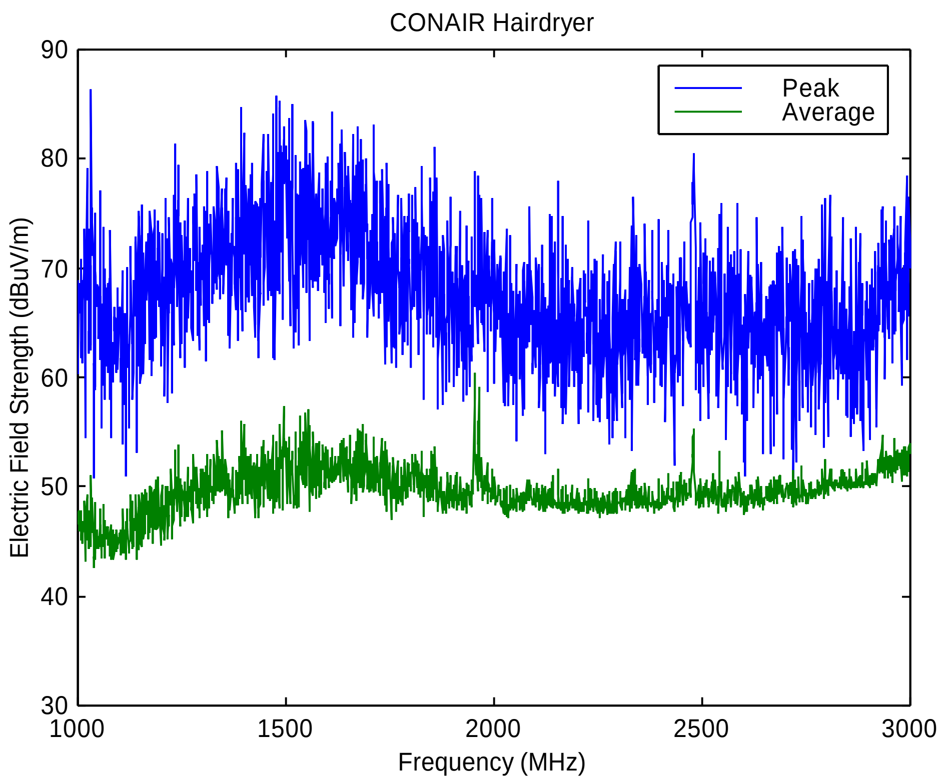
[44] See ANSI C63.4 and www.fcc.gov/Bureaus/Engineering_Technology/Orders/1997/fcc97114.txt


Sun Workstation Motherboard
Peak
Average
Electric Field Strength (dBuV/m)
Frequency (MHz)
90
80
70
60
50
40
30
1000
1500
2000
2500
3000


Time Domain Corporation RadarVision
Peak
Average
Electric Field Strength (dBuV/m)
Frequency (MHz)
90
80
70
60
50
40
30
1000
1500
2000
2500
3000



Norelco Razor
Peak
Average
Electric Field Strength (dBuV/m)
Frequency (MHz)
90
80
70
60
50
40
30
1000
1500
2000
2500
3000



CONAIR Hairdryer
Peak
Average
Electric Field Strength (dBuV/m)
Frequency (MHz)
90
80
70
60
50
40
30
1000
1500
2000
2500
3000